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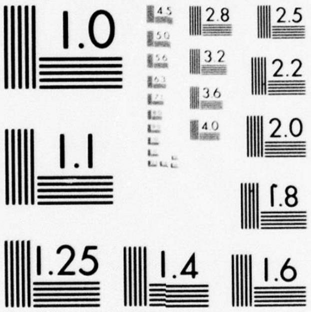

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USER DELAY COST MODEL AND FACILITIES MAINTENANCE COST MODEL FOR A TERMINAL CONTROL AREA

Volume I : Model Formulation and Demonstration

L. B. Greene
J. Witt
M. Sternberg-Powidzki

ARINC RESEARCH CORPORATION
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Airway Facilities Service
Washington DC 20590

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16. Abstract

The User Delay Cost Model (UDCM) is a Monte Carlo computer simulation of essential aspects of Terminal Control Area (TCA air traffic movements that would be affected by facility outages. The model can also evaluate delay effects due to other factors, such as weather, aircraft schedule intensity, and approach minima. Although the Boston TCA was selected as the study vehicle for development and demonstration, the model is structured so that it can be applied to other TCAs.

The Facility Maintenance Cost Model (FMCM) is designed to evaluate the expected annual labor cost of maintaining FAA facilities within a maintenance sector. The model was developed for time-share computer application and can evaluate both the preventive maintenance and corrective maintenance required by any single facility (e.g., a visual omni-range or VOR), accumulate staffing and cost data on similar facilities (e.g., all VORs) within the specified maintenance sector, and then evaluate all other types of facilities (e.g., Airport Surveillance Radar, Outer Markers) within the sector.

This is the first of three volumes. Volume II is a user's manual for the user delay cost model. Volume III is a user's manual for the facilities maintenance cost model.

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PREFACE

The Federal Aviation Administration is responsible for operating and maintaining the airway facilities of the National Aviation System. The magnitude of annual operating and maintenance costs is such that means for reducing these costs are being sought.

This report documents the results of a study to model the relationship between airway facility maintenance practices and (1) aircraft delays in terminal areas, and (2) maintenance costs.

These models are intended to serve as tools for estimating the impact on system users and system operators of proposed maintenance cost reduction initiatives.

The models were formulated, demonstrated, and documented by ARINC Research Corporation under contract to the Transportation Systems Center. Mr. F. Frankel of the Transportation Systems Center provided the technical guidance. The dedication and expertise of Mr. L. B. Greene, Dr. J. Witt, and Mr. M. Sternberg-Powidzki of ARINC Research is acknowledged to be the major contribution to this work.

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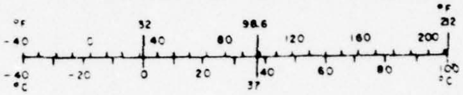
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
	LENGTH			
in	inches	2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
	AREA			
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
	MASS (weight)			
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
	VOLUME			
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
	TEMPERATURE (exact)			
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
	LENGTH			
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
	AREA			
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
	MASS (weight)			
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
	VOLUME			
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
	TEMPERATURE (exact)			
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



SUMMARY

1. OBJECTIVE

The objective of this study is to provide the Federal Aviation Administration (FAA) with two analytical tools to be used in support of its efforts to control maintenance costs. This objective has been achieved by developing, demonstrating, and documenting two such models for the Transportation Systems Center (TSC). The application of these models for FAA maintenance planning is beyond the scope of the contract work.

2. BACKGROUND

The volume of air traffic that flows safely and efficiently through the network of airway facilities spanning the United States is enormous and constantly growing. In 1975, Chicago O'Hare International Airport alone handled 690,419 aircraft operations. To support this level of activity, the FAA maintains more than 100 distinct types of airway facilities, e.g., VHF Omnidirectional Ranges (VOR), Airport Surveillance Radars (ASR), etc. In 1975, FAA maintenance was performed by a 10,000-man force assigned to 140 maintenance sectors, at a total cost of $390 million.

The FAA's Airway Facilities (AF) Service, in an effort to reduce this heavy expenditure of funds, commissioned TSC to investigate means of reducing these costs without imposing excessive delays on the user community. A constraint on this investigation was that, regardless of other considerations, safety must not be reduced.

In June 1975, TSC and ARINC Research Corporation together prepared an approach to the problem, and this approach was incorporated in the ARINC Research proposal to assist TSC in its investigation. The approach recognizes that the FAA can vary certain facility-maintenance policy decisions, e.g., preventive maintenance (PM) practices. Such variation will affect (1) the cost of facility maintenance and (2) facility availability. The variation in facility availability may affect the user community by causing changes in the delays induced by normal conditions of weather and schedule. TSC retained ARINC Research to develop two models

to focus on the varying costs of maintaining the airway facilities with changes in maintenance procedures and the concomitant delay costs experienced by the users.

3. MODEL SUMMARIES

3.1 User Delay Cost Model

One of the two models is the User Delay Cost Model (UDCM), designed to estimate delays to the user community due to facility outage and other factors. Originally, it was intended that the UDCM output would be dollar costs to the user community, divided into four classes: air carriers, air taxis, general aviation, and military aircraft. Subsequently, TSC and ARINC Research agreed that numerical delay measures would be more appropriate since they would make the model independent of cost factors, which could be expected to fluctuate with changing economic conditions. Costs to each group can be calculated by using delay measures generated by the model and cost factors appropriate to the user class.

The model is a Monte Carlo computer simulation of essential aspects of air traffic movement in and around a Terminal Control Area (TCA), with emphasis on the effects of facility outage. The Boston TCA (Logan Airport and several secondary airports) has been used as a guide for the model development. The model combines the three primary stochastic processes that induce user delays:

Facility outage

Traffic intensity

Weather.

The underlying premise of the model is that these three factors are intrinsically interrelated in the creation of delay and that the only way delay can be attributed to any single factor is to hold the other two constant and measure the differential delay caused by variation of the third. It can be seen that the differential delay associated with a facility outage depends, therefore, not only on the change of facility status but also on the existing weather conditions and traffic intensity. Historical weather data for Logan are already incorporated in the model, and the model will accept various aircraft traffic inputs. After delays are initially measured, several options are available for assessing the impact of facility outage. One or more facilities can be taken out of the system, e.g., the ASR, to determine the consequences of total unavailability. An alternative method is to assign values of Mean Time Between Outages (MTBO) and Mean Time To Restore (MTTR) to all facilities simulated in the model and let the model treat the outage and restoration times as random variables.

The model logic duplicates the complex rules and procedures that govern the movement of aircraft as a function of the aircraft traffic intensity, the status of FAA facilities, and the prevailing weather.

The basic questions that the model is concerned with in moving an aircraft are as follows:

Will the aircraft traffic exceed the instantaneous traffic-handling capability of a controller (controller capacity)?

Will aircraft separation be in conformance with FAA standards? The standards depend on the status of FAA facilities, the weather, and aircraft weight.

Can the aircraft land? The answer to this question depends on the status of FAA approach facilities and the weather.

A large number of detailed conditions or factors are considered in resolving these three key questions. For example, aircraft weight is used to determine landing separation criteria. Approach category and weather conditions establish landing minima. In addition, many runways and combinations of facilities are considered. The model has been developed to consider the above issues in some detail. To expedite the model development and its execution time, however, it was decided not to simulate every step-by-step command (e.g., heading vectors) that a controller issues to an aircraft but rather the overall set of rules being followed in generating these commands.

Although the model was designed to assess the impact of changing facility availabilities on user delays, it was recognized during the development process that the model would provide the ability to evaluate a number of additional issues. Therefore, the UDCM can be used to analyze the differential delays induced not only by facility outage but also by the effect of aircraft schedule and weather variations, as well as by a host of related factors. Any questions or issues affecting the following may be addressed easily with the model:

Spacing in final approach

Number of aircraft a controller can handle simultaneously

Landing approach minima.

For example, the model can answer questions such as "what would be the benefit (as measured by reductions in aircraft delay) of increasing the numbers of aircraft a controller could handle safely?" or "what is the benefit of installing a new facility having different characteristics (e.g., an ILS)?"

3.2 Facility Maintenance Cost Model

The second model, the Facility Maintenance Cost Model (FMCM), evaluates the expected annual labor cost and staffing requirements of maintaining FAA facilities within a maintenance sector. Developed for time-share computer application, it will evaluate both the preventive maintenance (PM) and corrective maintenance (CM) required by any single facility (e.g., a VOR), accumulate staffing and cost data on similar facilities (e.g., all VORs) within the specified maintenance sector, and then accumulate staffing and cost data for other types of facilities (e.g., ASRs, outer markers) within the sector.

The specific maintenance sector and facility types to be evaluated are specified as terminal inputs during program execution. An input file containing the pertinent data on facilities (e.g., type, reliability data, frequency and times of preventive maintenance) common to all sectors is automatically called and read at the beginning of the main program execution. The sector file, identified by terminal input, identifies the numbers of like facilities within the sector for each facility type, along with their restoration levels and manpower staffing criteria, and provides the remaining data necessary for evaluating the maintenance costs for the sector of interest.

The principal model outputs include the expected annual cost of maintaining a specific facility type within a sector, the required number of personnel by skill level for that facility type, the cost of preventive maintenance and corrective maintenance, and the costs of callbacks. The model also provides similar cost and labor data on the total of all facilities within the sector, including management/support personnel requirements and costs.

3.3 Potential Use of the Models

It is expected that the UDCM and the FMCM will ultimately be used together and in conjunction with a yet-to-be-developed Facilities Availability Model (FAM) as shown in Figure S-1. As a function of equipment data and maintenance scenarios, the output of the FAM would be a generalized measure of facility and sector availability, as well as reliability and maintainability measures to be used as partial inputs to the UDCM and FMCM. The three models could then jointly determine cost and availability relationships for cost and benefit trade-off analyses.

Models such as the UDCM, the FMCM, and the FAM require valid data if they are to provide reliable predictions. A Maintenance Management Information System would be valuable in the application of the UDCM and FMCM and in the future joint use of the FAM. Although these validated data were not available, demonstrations of the UDCM and FMCM have shown that they exhibit reasonable responses to typical input data variations.

4. RECOMMENDATIONS

The UDCM and FMCM have been successfully demonstrated and have exhibited their potential for future utilization. It is the opinion of ARINC Research Corporation that additional work would be desirable to accomplish the following:

Enlarge the scope of applicability of the present models

Create the Facilities Availability Model

Design and construct an FAA Maintenance Management Information System to support the model application effort

Apply the models to evaluate potential reductions in FAA maintenance costs.

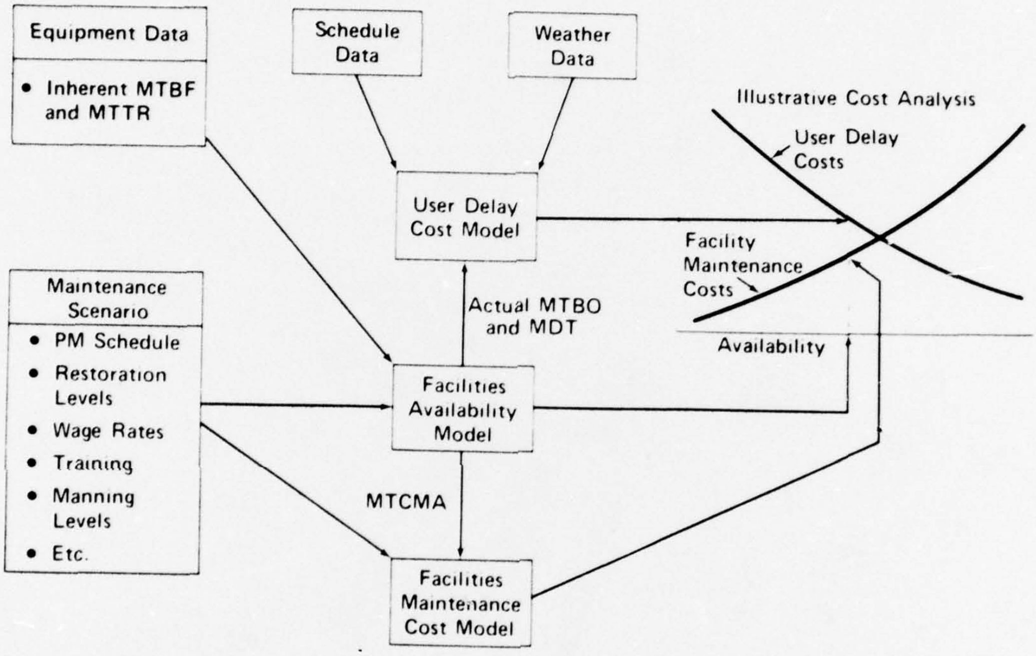


Figure S-1. MODEL REQUIREMENTS FOR ANALYZING COSTS TO THE FAA AND THE USER COMMUNITY AS A FUNCTION OF FACILITY AVAILABILITY

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CHAPTER ONE

INTRODUCTION

The volume of air traffic that flows safely and efficiently through the network of airways facilities spanning the United States is huge, and growing. Chicago O'Hare International Airport alone, in 1975, handled 690,419 aircraft operations, of which 577,283 involved air carriers. To support this level of operations, the Federal Aviation Administration (FAA) maintains 113 distinct types of airway facilities. FAA maintenance was performed in 1975 by a 10,000-man force assigned to 140 maintenance sectors, at a total cost of $390 million.

The FAA's Airway Facilities (AF) Services, in an effort to reduce this heavy expenditure of funds, commissioned the Transportation Systems Center (TSC) to investigate means of reducing these costs without simultaneously imposing excessive delays on the user community. A constraint on this investigation was that regardless of other considerations, the level of safety must not be reduced.

In June 1975, TSC and ARINC Research Corporation together prepared an approach to the problem that was incorporated in the ARINC Research proposal to assist TSC in its investigation. This approach recognizes that the FAA can vary certain facility-maintenance policy decisions, preventive maintenance (PM) practices, and many other activities. Such variation will affect (1) the cost of facility maintenance and (2) facility availability. The variation in facility availability will affect the user community by causing changes in the delays induced by normal conditions of weather and schedule. TSC retained ARINC Research to develop two models to focus on the varying costs of maintaining the airways facilities with changes in maintenance procedures and the concomitant delay costs experienced by the users.

1.1 STUDY PURPOSE

The purpose of this study is to provide the FAA with two analytical tools to be used in support of its objective of reducing maintenance costs. This purpose has been achieved by developing, demonstrating, and documenting two cost models for TSC.

The first of the two models presented in this report is the User Delay Cost Model (UDCM), designed to estimate delays to the user community due to facility outage and other factors. The user community is divided into four classes: air carriers, air taxis, general aviation, and military aircraft. Originally, it was intended that the output of the UDCM would be dollar costs to the user classes caused by delays. Subsequently, it was decided with TSC that a more appropriate output form would be a set of delay measures expressed in numerical and physical terms rather than in terms of dollars. This makes the model independent of cost factors, which may be expected to fluctuate with changing economic conditions. Costs to each group can be calculated by using delay measures generated by the model and cost factors appropriate to the user class. The model is a Monte Carlo computer simulation of essential aspects of air traffic movement in the Boston Traffic Control Area that are affected by facility outage.

The second model, the Facility Maintenance Cost Model (FMCM), is designed to evaluate the expected staffing requirements and annual labor cost of maintaining FAA facilities within a maintenance sector. It is constructed to allow expansion to include nonlabor cost elements and to encompass multi-year (or life cycle) costs. The model has been developed for time-share computer application. It will evaluate both the preventive maintenance and corrective maintenance required by any single facility (e.g., all VORs) within the specified maintenance sector, and then evaluate all other types of facilities (e.g., ASRs, Outer Markers) within the sector.

Ultimately it is expected that the UDCM and the FMCM will be used jointly and in conjunction with a yet to be developed Facilities Availability Model, as shown in Figure 1-1.

The UDCM accepts schedule and weather data inputs as well as predicted failure and repair parameters from the Facilities Availability Model (FAM). Mean Time Between Outages (MTBO) and Mean Downtime (MDT) will be the principal parameters for predicting user delay cost as a function of availability. The FMCM inputs, principally Mean Time to Corrective Maintenance Action (MTCMA) and maintenance scenario options, will be combined in the model to predict facility maintenance cost as a function of availability. When these two functional relationships have been developed, as suggested by the graph in Figure 1-1, an optimal level of facility availability can be calculated. The concept of availability embodied in this figure is a generalized one. It can be thought of as either the availability of a single facility or a weighted combination of facility availabilities to represent, for example, a sector availability.

1.2 ORGANIZATION OF REPORT

This report is presented in seven chapters and two appendixes. Following this introduction, Chapter Two presents the overall technical approach, including a description of and justification for the assumptions made in the construction of the models, and the limitations to model usage. This chapter also contains a narrative description of project activities.

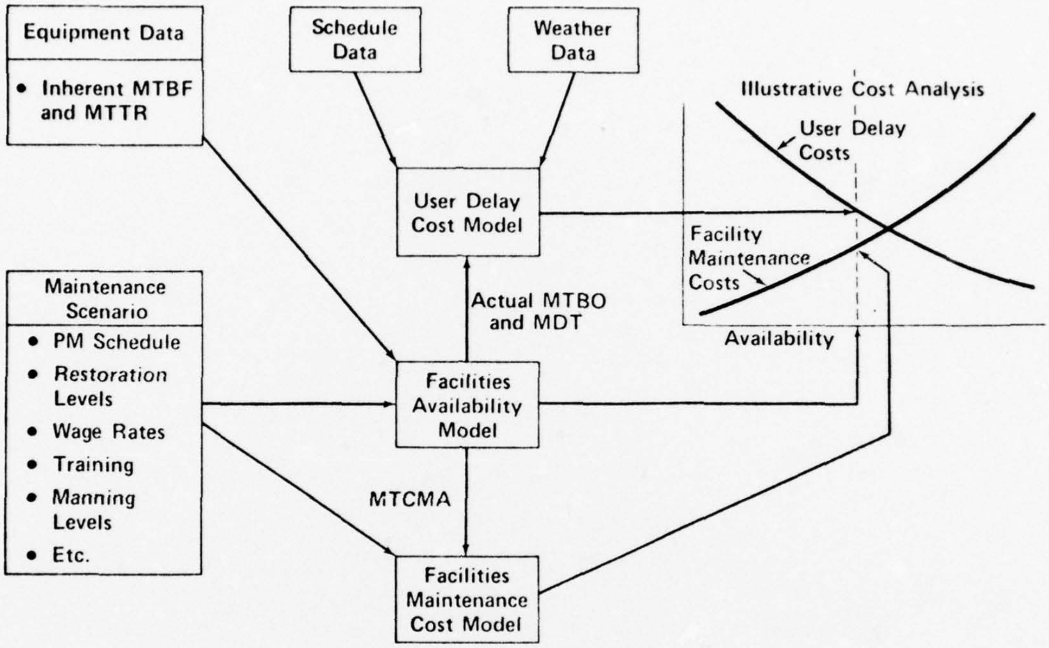

Figure 1-1. MODEL REQUIREMENTS FOR ANALYZING COSTS TO THE FAA AND THE USER COMMUNITY AS A FUNCTION OF FACILITY AVAILABILITY

Chapters Three and Four report on the User Delay Cost Model. The development methodology, the subject of Chapter Three, includes an overview of model capabilities, the technical approach to model formulation, model limitations, data required to exercise the model, and a description of model outputs.

Chapter Four describes the UDCM demonstration and provides an analysis of the demonstration results.

Chapters Five and Six report on the Facilities Maintenance Cost Model. Chapter Five includes an overview of model capabilities, technical approach to formulation, model inputs and outputs, model applications, and limitations. Chapter Six describes and analyzes the FMCM demonstration.

Chapter Seven presents the conclusions and recommendations resulting from this study, and suggests areas of effort for further development of the potential of these models.

A detailed description of the data required by the UDCM is provided in Appendix A; reference documents are listed in Appendix B.

CHAPTER TWO

OVERALL PROJECT TECHNICAL APPROACH

A model is an abstract representation of reality. It may be a set of mathematical expressions, as is the FMCM, or a computer simulation, as is the UDCM, or a "black box" with the contents unspecified. The most important property is that the outputs, or responses, are related to the inputs in a manner consistent with their real world counterparts. In order to achieve the desired degree of realism in the UDCM and FMCM, it was necessary first to identify those features of air operations and maintenance practice which were to be modeled and determine how they were related to delay and cost.

2.1 MODEL DEVELOPMENT

The formulation of the models was based on interviews with personnel at the Boston Logan tower and maintenance personnel in the New England Region, and on observations of operations in the Logan tower, to identify those elements of maintenance and operations to which the models would be most responsive. Initial visits were followed by research into standard operating procedures. A number of manuals and studies were consulted, both those governing the entire FAA and those peculiar to Boston. These are identified in the Reference section of this report.

The field observations, supplemented by detailed telephone interviews, were combined with the research to produce an outline for the structure of the models. As these structures were developed, it became apparent that certain limits on the scope and complexity of the models would be necessary if the cost and time constraints were to be met. Most of the key model limitations were reviewed by TSC or Boston tower personnel.

The models were then programmed and tested incrementally, especially the UDCM, as modules were completed. As the models were being assembled, data were collected jointly by TSC and ARINC Research. This concurrent model construction and data collection assured that data required by the model were or could be made available. It should be noted, however, that data collection was not a contractual responsibility of ARINC Research and that while every effort was made to provide accurate data, some of the inputs to the models were estimated for demonstration purposes. These instances are noted throughout this report as appropriate.

The models were tested by using facilities at both TSC and ARINC Research for the UDCM, and at ARINC Research (CDC Kronos time-sharing system) for the FMCM.

2.2 STUDY GUIDELINES AND ASSUMPTIONS

After Terminal Radar Control (TRACON) facilities and tower operations were observed, maintenance personnel interviewed, and the required additional research performed, two important model guidelines were identified:

The models were to have the capability to describe any TCA or maintenance sector parametrically.

Only first-order-of-magnitude inputs were to be considered.

The first of these guidelines assures model flexibility. Thus by changing the input data set, the models can be made to represent any TCA or sector. Adherence to the second guideline prevented unnecessary proliferation of modeling detail.

The specific model assumptions described in the following paragraphs were made to conform with these guidelines.

2.2.1 UDCM Assumptions

The most important assumptions adopted for the UDCM are the following (others, less fundamental, are described and discussed in this report as they are encountered):

Facility outage interacts with weather conditions and aircraft schedule (level of aircraft operations) to impose delays on the using communities.

Separation of aircraft in the TCA will be maintained by arrival and departure controllers and by aircraft pilots.

Aircraft malfunctions are not considered.

In the first assumption it is implicit that delay is jointly determined by these three factors; it is meaningless to attribute some level of delay to one factor without at the same time considering the other two.

The second assumption makes it unnecessary for the logic of the model to regulate speed, altitude, and heading of aircraft in the model to assure lateral and vertical separation.

2.2.2 FMCM Assumptions

The principal assumption of the FMCM concerns labor costs. Since labor costs constitute 80 percent of total maintenance cost, this is the first-order-of-magnitude input and is the only cost factor affecting the FMCM.

CHAPTER THREE

USER DELAY COST MODEL

3.1 DESCRIPTION OF BOSTON TCA

The Boston Terminal Control Area is a typical high-volume TCA, and for this reason was chosen by the FAA as the guide for development of the UDCM. A broad overview of the Boston TCA is presented here in preparation for the discussion of the UDCM particulars.

The Boston TCA is a positively controlled airspace, centered approximately on Logan Airport, about 40 miles in diameter. Figure 3-1 depicts the Boston TCA. The ceiling of the TCA is 7000 feet above mean sea level (MSL), while the floor varies from the surface, near Logan, to 4000 feet MSL elsewhere.

Within the TCA, since it is a positively controlled airspace, all aircraft are subject to the operating requirements specified in Part 91 of the Federal Aviation Regulations (FARs). Aircraft desiring to pass through the TCA must request permission, which may be denied on the basis of traffic load within the TCA. Air traffic control service extends outside the TCA to accommodate the aircraft crossing TCA boundaries. Although an aircraft may request entry at any point on the TCA boundary, most will be flying the airways and will appear at standard boundary entry points. These points have associated with them holding fixes, or patterns, at which inbound traffic may be held, or stacked, until they can be accepted and handled by one of the three arrival radar (AR) controllers who operate in the Boston Terminal Radar Control (TRACON) Facility. There are five such fixes associated with the Boston TCA: Manjo, Millis, Bridgewater, Skipper, and Lawrence. They lie about 20 to 25 nautical miles from Logan and are depicted in Figure 3-1 in their approximate locations as race-track patterns, with the arrows showing the holding direction.

When an aircraft approaches the Boston TCA on an IFR flight plan, it will normally be under the control of the Boston Air Route Traffic Control Center (ARTCC). It will be handed off to the Boston TRACON at some point outside the TCA but inbound to one of the holding fixes. If there is a light traffic load, and if traffic is moving well, the aircraft will be vectored without delay to a point where it can commence an approach to the runway in use. If, on the other hand, the aircraft cannot be accepted -- because the controller already has his hands full, there is inadequate

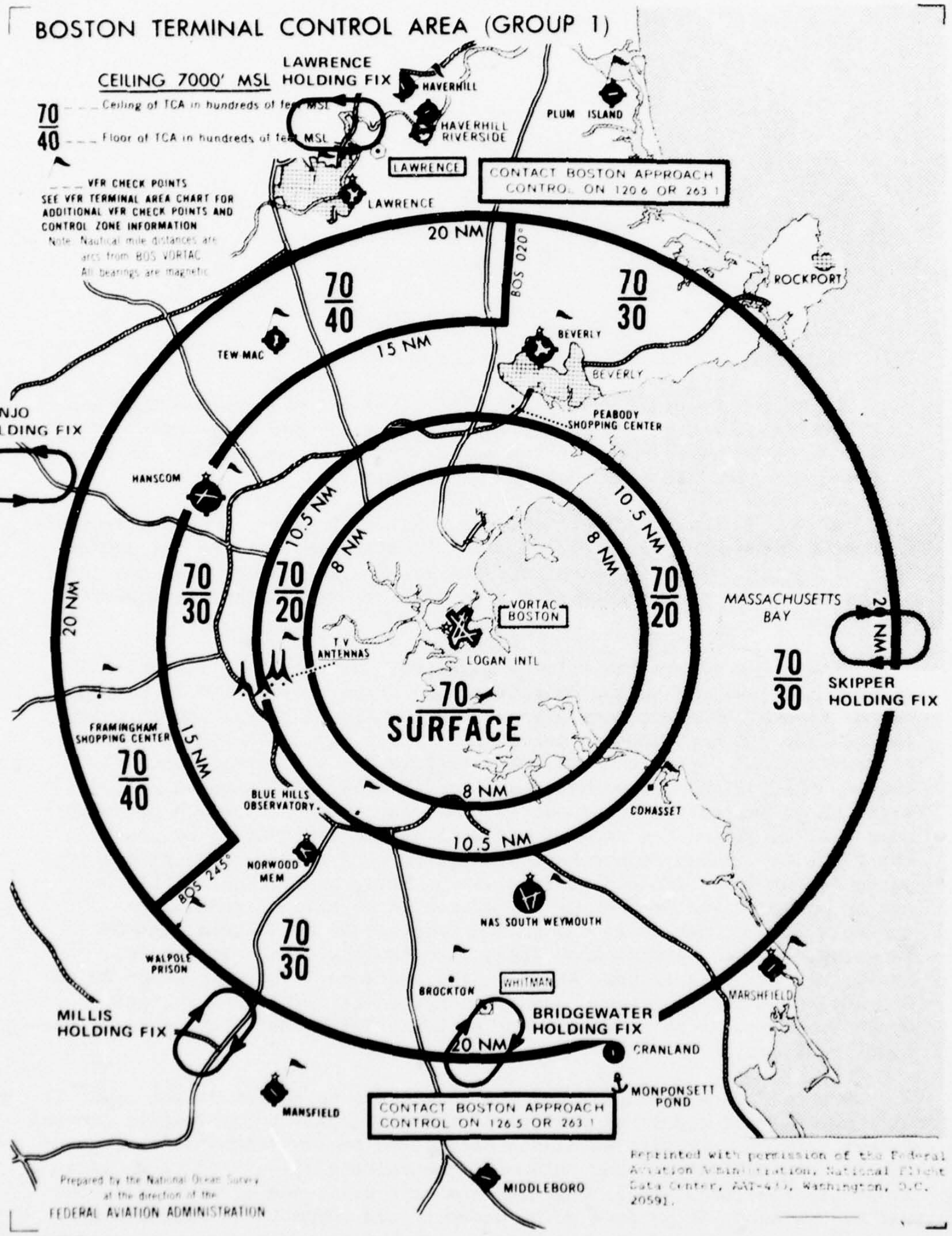

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Figure 3-1. BOSTON TERMINAL CONTROL AREA separation between the aircraft currently entering and those ahead, or the weather is below minima and no one is landing -- the aircraft will be advised to hold. At Boston, aircraft holding will normally be under TRACON control at altitudes up to some agreed upon level, about 9000 feet, and under ARTCC control above that. If a long delay is anticipated, a pilot will make a decision to wait for a certain period of time or possibly divert to his alternate airport.

Departing aircraft are similarly controlled and handed off to ARTCC if on an IFR flight plan or cleared to exit the TCA if on a VFR flight plan.

There are three ARs in the Boston TRACON. Two of them handle traffic inbound to Logan and to secondary airports south of Boston. The third handles inbound traffic to secondary airports, generally north of Logan, in what is known as the Bedford Sector. Similarly, there are departure radar (DR) controllers who handle outbound traffic. In order to assess the relative importance of traffic to Logan and the secondary airports, it is pointed out that in 1975, 83 percent of the instrument approaches made in the TCA were made into Logan.

Control is exercised primarily by radar vectors given to the aircraft by direct voice command from the AR or DR. The principal radar in use in the Boston TCA is the Airport Surveillance Radar (ASR-7), located at Logan airport. Since all aircraft operating in a TCA are required to be equipped with a transponder beacon, the beacon radar, sometimes called the Secondary Radar (SECRA), can also provide position information from which vectors can be generated.

Both of these radars interface with the ARTS-III computer, which receives the basic radar data via coaxial cables from the two radars. The data are digitized and displayed to the controller. The controller sees an enhanced image of the target, target identity, altitude (from digital altimeter response from the aircraft), aircraft speed (generated by the ARTS-III), and a number of other useful visual data. In the event the ASR goes out of service, the SECRA can provide most of the data to the controller except target information on nonbeacon-equipped aircraft that may be above or below the TCA. If both the ASR and SECRA are inoperative, a somewhat reduced radar capability is available from the Winthrop Air Route Surveillance Radar (ARSR), which services the Boston ARTCC and is located at nearby Winthrop. No computer processing is available with this facility; all that is seen is raw video at a somewhat slower information rate than that provided by the ASR and SECRA.

If no radar service is available, all separation must be maintained by pilots and controllers, using only navigation aids such as radio beacons and distance measuring equipments. This is a seriously degraded mode of operation for a busy airport. Fortunately, circumstances leading to such a degraded mode of operation are rare.

This, in broad outline, is the "real world" situation in the Boston TCA. The remainder of this chapter is devoted to an explanation of how the UDCM simulates this air traffic control environment.

3.2 OVERVIEW OF MODEL AND ITS CAPABILITIES

The UDCM is a Monte Carlo simulation model* that combines the three primary stochastic processes that induce user delays:

Facility outage

Traffic intensity

Weather.

The underlying premise of the model is that these three factors are intrinsically interrelated in the creation of delay and that the only way delay can be attributed to any one is to hold two constant and measure the differential delay caused by variations of the third. It is easily seen, therefore, that the differential delay associated with a facility outage depends not only on the change of facility status but also on the existing weather conditions and traffic intensity. The weather and levels of aircraft activity can be set in any manner, but a large quantity of recent historical weather data for Logan is already incorporated in the model. After delays are thus initially measured, several options are available for assessing the impact of facility outage. One or more facilities can be taken out of the system -- e.g., the Airport Surveillance Radar (ASR) -- to determine the consequences of total nonavailability. An alternative method would be to assign values of Mean Time Between Outages (MTBO) and Mean Time to Restore (MTTR) to all facilities simulated in the model and let the model treat the outage and restoration times as random variables.

---

*A Monte Carlo simulation model is a computer-based tool used to analyze complex systems which in real life have outcomes, products, or outputs that are subject to chance. For example, the number of aircraft diverted from Logan on any particular day is a random quantity that is dependent on the complex interaction of a large number of other independent random, or chance, events. If the probabilities of all the determining events are known, as well as the manner of their interaction, then the probability of the dependent event can be estimated, even when it cannot be calculated mathematically. The essential act that the computer performs is to sequence through the network of events or decision points to simulate and evaluate the outcomes. It does this by randomly selecting at each decision point a number from a set of 1000 equally likely numbers from 1 to 1000. This corresponds to selecting a uniform random number from the interval 0 to 1.0. Repeated reference will be made to this process in this chapter.

3.3 TECHNICAL APPROACH TO MODEL FORMULATION

The model logic duplicates the complex rules and procedures that govern the movement of aircraft as a function of the aircraft traffic intensity, the status of FAA facilities, and the prevailing weather. An aircraft bound for Logan is generated at the boundary of the Boston TCA (at one of the five holding fixes), and its movement from there to Logan is simulated. Aircraft going to secondary airports appear in the model as if they were at the destination airport. For aircraft landing at Logan, a randomized turnaround time is used to schedule a subsequent departure. Aircraft departing from secondary airports are not simulated.

The basic questions that the model is concerned with in moving an aircraft are:

1. Will this additional aircraft exceed the instantaneous traffic-handling capability of a controller (controller capacity)?
2. Will aircraft separation be in conformance with FAA standards? The standards are dependent on the status of FAA facilities, the weather, and aircraft weight.
3. Can the aircraft land? This is dependent upon the status of FAA approach facilities and the weather.

As will be shown in the ensuing discussions of the model, there are a large number of detailed conditions or factors that must be considered in resolving these three key questions. For example, the aircraft weight and approach category are needed to establish separation criteria, as are minimum weather conditions for landing. There are also many runways and combinations of facility availabilities to be considered. The model has been developed to consider these issues in some detail. To expedite the model development and its execution time, however, it was decided not to simulate every step-by-step command (e.g., heading vectors) that a controller issues to an aircraft but rather the overall set of rules that are being obeyed in generating these commands.

Figure 3-2 is a generalized flow diagram for the UDCM. It illustrates the logical relationships among the main decision processes and files that constitute the model. The weather assumes a major role in the model, as it does in nature. The state of the weather determines directly the level of air activity, especially among general aviation users since the level of general aviation activity usually declines during actual instrument conditions. It also determines in large part the runway in use, which has an impact on the kinds of approaches, which, interacting with the weather, determine the landing minima. For these reasons, Figure 3-2 shows weather generation as the first, or driving, model element.

The second program element is aircraft generation. This consists of determining, by random processes, as a function of weather conditions (IFR or VFR) and time of day, the time of next arriving aircraft, type of

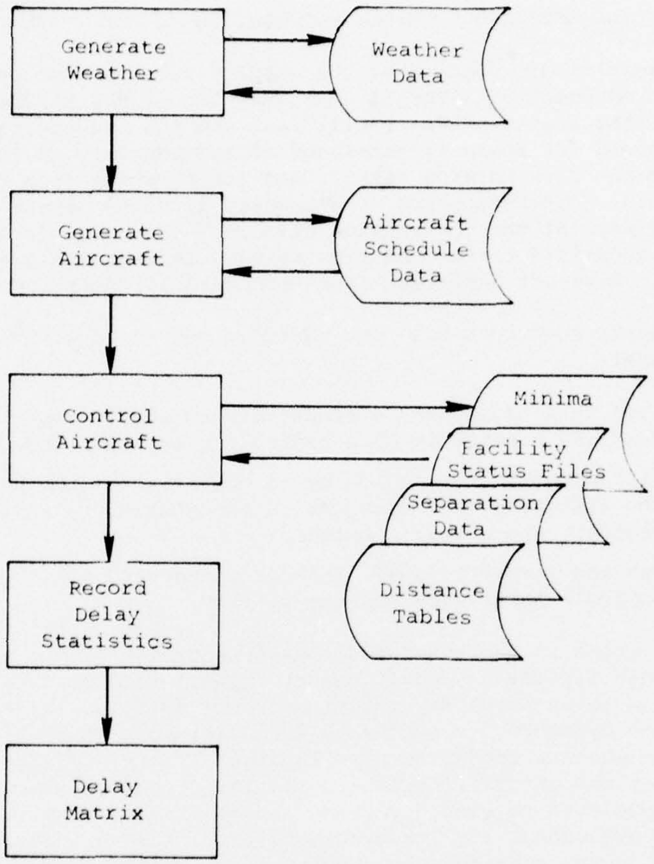

Figure 3-2. GENERALIZED FLOW CHART FOR THE UDCM

aircraft (air carrier, air taxi, general aviation, or military), weight (small, large, or heavy), landing approach category (A,B,C, or D)*, destination, speed, and original position when first considered by the model.

The third program element, aircraft control, is more complex than the first two and is the heart of the model. It addresses, as a logical

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*See Section 3.3.2.5 for an explanation of landing approach categories.

unit, the five questions that must be answered by tower and air control personnel in real life and by the model:

> What is the preferred landing or takeoff runway, taking into account wind speed and direction and other priorities, such as noise abatement?
>
> If there are one or more instrument approaches for the preferred runway, is there at least one instrument approach for which all facilities required for landing are "up"?
>
> Is the weather such that, for the preferred runway, it is above minima for at least one of the available approaches for the preferred runway?
>
> Having a runway and usable instrument approach, how should the aircraft be moved to the runway and proper separation established in the final approach?
>
> For aircraft taking off from Logan, how should proper separation be established between landing aircraft and other aircraft taking off?

There are, of course, many variations and details related to how these questions are dealt with and to other necessary program tasks. These are discussed in Section 3.3.3. The remaining model elements shown in Figure 3-2 correspond to input data files required to exercise the model and record the accumulation of delay statistics.

Although the model was developed to assess the impact of changing facility availabilities on user delays, it was recognized during model development that it would provide the ability to evaluate a number of additional issues as well. Therefore, the capabilities discussed in the following paragraphs should be kept in mind when the features of the model are being assessed.

The UDCM can be used to analyze the differential delays induced not only by facility outage but also by the effect of aircraft schedule and weather variations, as well as by a host of other related factors. For example, at Logan there is no ILS on runway 27. A typical question might be "What would be the delay impact of equipping runway 27 with an ILS?" All that is required to answer this question, using the present model, is to insert a set of ILS minima for a straight-in approach on 27 in the minima table. It is easy to extend this argument to "What would be the effect of replacing the ILS on runway 4R with a Category III ILS or the Microwave Landing System?" Here, too, all that is required is a simple change in the minima table.

Many other questions and issues may be addressed. In fact, anything that affects spacing in final approach, number of aircraft a controller can handle simultaneously, or minima can be examined by simple input-data changes. It is emphasized, however, that the model cannot determine what these data changes will be; this must be done by analysis external to the model. This being the case, the model could answer the question "What would be the benefit (as measured by aircraft delay reductions) of increasing the number of aircraft per controller from 10 to 20?", without regard for how it was to be done. If the savings were appreciable, this could be taken as justification to examine the feasibility of attempting to achieve this increased controller capacity.

The model can also serve as an aid in airport design and layout, such as runway orientation. In this use, in particular, accurate weather data are required for the weather module; but with such data, it would be possible to decide whether a runway array of (4,22), (15,33), (9,27), for example, is better than (5,23), (17,35), (11,22), where the numbers in parentheses are runway directions in tens of degrees, magnetic.

The model is not all-encompassing, but enlarging the basic logic makes many new options possible at little cost in terms of incremental analysis and additional modeling.

3.3.1 Weather Generation

Figure 3-3 is a flow diagram of the weather module, in which it is seen that separate weather data tables are used in the model for night and day. The model checks the time and then by random processes determines, in order, the wind direction, wind speed, ceiling, and visibility. The following assumptions were used in formulating this module:

> Weather phenomena are associated with the presence and movement of pressure systems. Wind direction and velocity are a direct consequence of these movements and are correlated with one another.
>
> Cloud cover and height are, through the movement of pressure systems, correlated with wind direction and velocity.
>
> Visibility is correlated with wind direction and ceiling height.
>
> There is a tendency to persistence in weather conditions.

These assumptions, while certainly not an exhaustive set, are deemed essential to a realistic model, or simulation, of weather phenomena (wind direction, velocity, ceiling, and visibility) in any locale. Fortunately, a good data base is available from Boston upon which a simulation of these phenomena can be based.*

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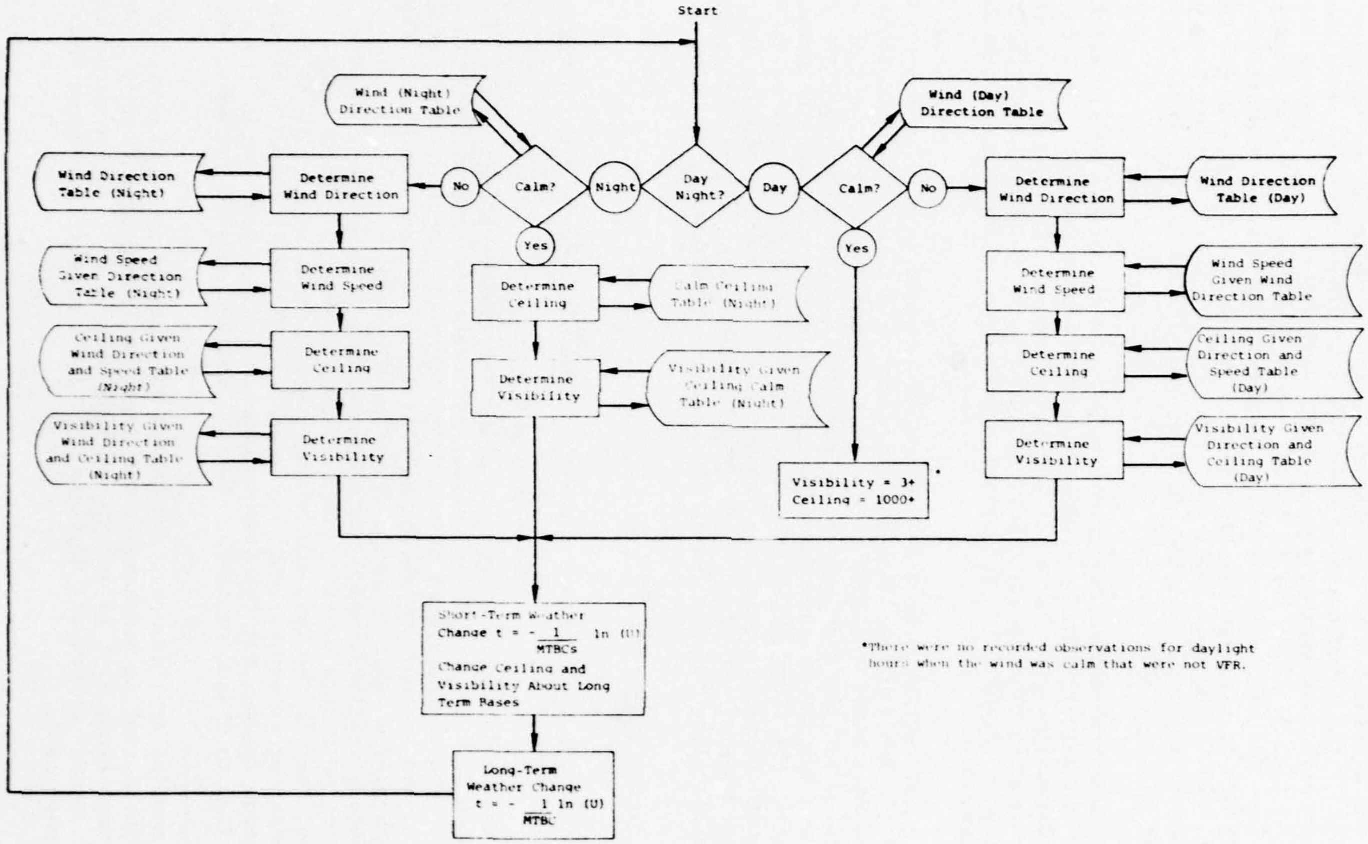
*A statistical summary prepared by the National Climatic Center, Asheville, North Carolina, "Special Ceiling-Visibility Wind Tabulation", was used for Boston. The period of observation was from January 1970 through December 1974. Observations were made for daytime hours at 1000, 1300, 1600, and 1900 Local Standard Time (LST), and for nighttime hours at 2200, 0100, 0400, and 0700 LST. The data are published in two separate sets of tables (night and day), each with 7304 observations.



*There were no recorded observations for daylight hours when the wind was calm that were not VFR.

Figure 3-3. WEATHER MODULE LOGIC

The available data, samples of which are presented in Appendix A, consist of the frequencies of occurrence of wind direction, on a 16-point compass with associated frequencies of wind velocity, grouped as follows: 1 to 4, 5 to 9, 10 to 14, 15 to 29, and 30+ knots, as well as conditions of calm. For each wind direction-velocity combination, frequencies of occurrence of ceilings are provided. Ceilings are grouped as follows: 1000+, 600 to 900, 500, 400, 300, 200, and 100 feet. Visibilities are grouped as follows: 0 to 1/4, 5/16 to 1/2, 5/8 to 7/8, 1, 1-1/4 to 1-1/2, and 3+ nautical miles.

These frequencies are presented as conditional probabilities; thus they allow the calculation, by randomizing on the unit interval, of a particular wind direction; and, given the wind direction, a wind speed; and, given the wind direction and speed, a ceiling; and, given the wind direction and ceiling, a visibility. The data are presented to the computer through input matrices.

A related issue is when and how to simulate changes in the prevailing weather. Two studies, also performed by the National Climatic Center, suggested a basis for such simulation*. Under the assumption that wind direction and speed determine, in part at least, ceiling and visibility, the data provide a basis for answering the question of when to vary the weather. The wind persistence data fit an exponential decay curve fairly well with a Mean Time Between Changes (MTBC) of about 3 hours. The weather module, therefore, defines an exponentially distributed random variable called Time to Change the Weather. Its density function is

$$f(t) = \frac{1}{MTBC} e^{-t/MTBC} . \tag{3-1}$$

A nominal value of 3 hours for MTBC has been selected on the basis of these studies.

The question of how much to allow the weather to vary, once the time has been decided, is not so obvious and bears some discussion. In general, except when thunderstorms or strong fronts pass a station, the variation in wind and weather is gradual and highly correlated with past history. For example, an abrupt change from VFR to zero-zero would be rare. A completely realistic model would capture this historicity; however, the creation of such a model is not necessary. What is needed instead is a model that in the long run produces statistical similarity to the phenomena of interest. This has been done by merely allowing the weather to change randomly at the time selected, i.e., randomizing on the exponential Time to Change variable. As an added refinement, the model allows for

---

*The studies are "Seasonal and Annual Persistence of Surface Wind Direction by Wind Speed" at Binghamton, New York, for the period January 1960 to December 1964, with 24 observations per day; and "Duration of High Surface Wind Speeds" at Oscoda, Michigan AFB, for the period November 1950 to December 1970.

small short-term variations. The model assumes that ceiling and visibility will vary uniformly about the basic "long term" values determined above. These "short term" variations are induced at times that are also exponentially distributed but with a nominal mean of 15 minutes. This is in conformance with observed short-term weather fluctuations and allows the model to simulate the conditions underlying a pilot's decision to wait for a short-term weather change if conditions are marginally below minima.

3.3.2 Aircraft Generation Module

The objective of the aircraft generation module is to create aircraft to be routed through the Boston TCA in the exercise of the model. Figure 3-4 displays the module logic.

Each aircraft will be defined in terms of the following set of descriptors:

1. Time of creation
2. Destination
3. Type
    - Air carrier
    - Air taxi
    - General aviation
    - Military
4. Origin
5. Aircraft characteristics
    - Weight
    - Landing approach category
    - Landing speed.

Sections 3.3.2.1 through 3.3.2.5 are discussions of how the model generates these aircraft descriptors.

3.3.2.1 Time of Next Aircraft Generation

Aircraft are assumed to appear in the model as a Poisson process. Within any given hour, e.g., from 001 to 0100, 0101 to 0200... 2301-2400, the arrival rate is considered constant, although the arrival rate for one hourly period will generally be different from that of another.

Arrival rates can also be expected to vary as a function of weather conditions. For example, since most general aviation activity decreases in IFR conditions, the arrival rate during any particular hour should be lower than for the same time of day under VFR conditions.

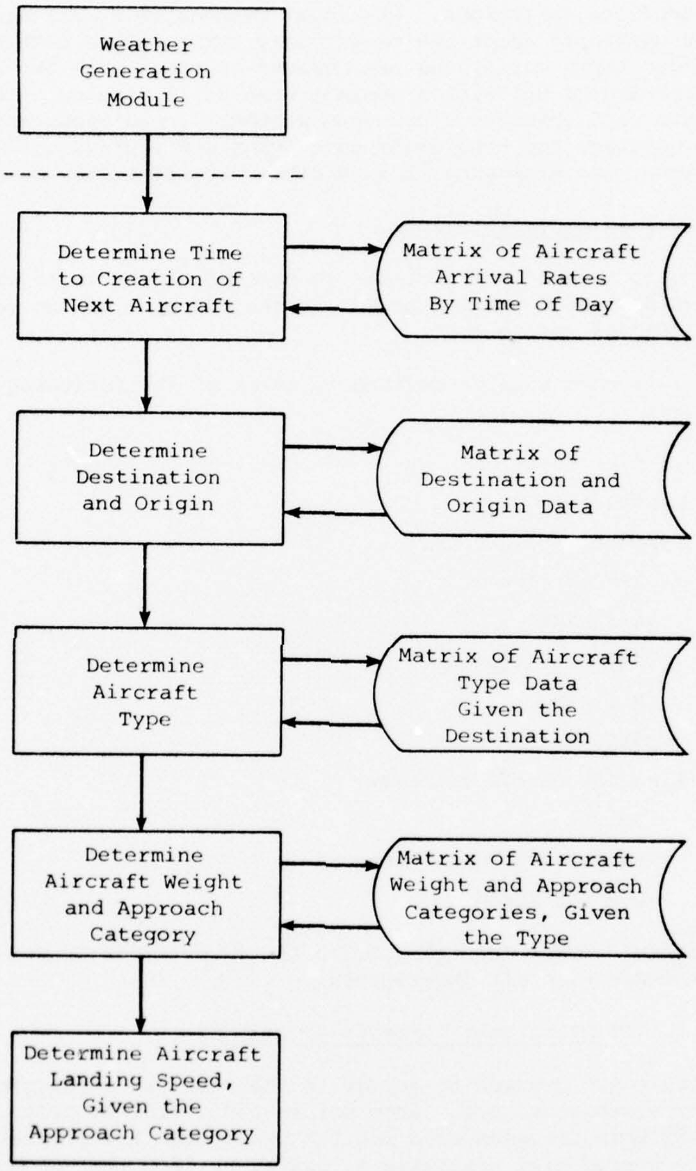


Figure 3-4. AIRCRAFT GENERATION MODULE LOGIC

The model, therefore, determines the time of generation of the next aircraft in the following way. First, the weather condition, whether IFR or VFR, is noted. This directs the program to the appropriate table containing arrival rates as a function of time of day. Entering this table with the time of day yields the number of aircraft expected to be generated during the current hour.

If λ_{jk} is the arrival rate during the j^{th} hour, where j=1 corresponds time 0001-0100, j=2 corresponds to 0101-0200 on up to j=24, and k=0 implies IFR and k=1 implies VFR, then the elapsed time to the appearance of the next aircraft is given by the expression,

$$t = \frac{-1}{\lambda_{jk}} \ell n(U), \tag{3-2}$$

where U is a random number uniformly distributed on the unit interval (0,1).

It was not the responsibility of ARINC Research to accumulate data to exercise the model. Even so, in order to demonstrate the model, arrival-rate data in some form had to be available to the program. Chapter Four of this report contains a discussion of the importance of aircraft arrival rates on model performance and accuracy. Appendix A contains a description of how the arrival rate data used in the model demonstration were actually obtained. These references will make clear how important accurate arrival rate data are, and how hard they are to obtain. It is thus important that, before the model is exercised for analysis, a good arrival-rate data base be developed. It is suggested that arrival-rate data be gathered for each destination airport in the area to be modeled, the Boston TCA in this case, and that the rates be observed and recorded as a function of time of day and by weather condition. Ideally, two matrices should be developed, one for IFR condition and one for VFR condition. Each matrix would have n rows, where n is the number of destination airports; and 24 columns, one for each hour of the day. Thus λ_{ijk} would be the arrival rate into the i^{th} airport during the j^{th} hour, under weather condition k (IFR or VFR). With these rates at hand, the overall arrival rate, referred to above as λ_{jk}, could be found by summing λ_{ijk} over i, thus

$$\lambda_{jk} = \sum_{i=1}^{n} \lambda_{ijk}. \tag{3-3}$$

3.3.2.2 Aircraft Destination

After an aircraft has been generated, it is necessary to determine the destination to which the aircraft will be assigned. The probability, P_i, that the aircraft will go to airport i is given by

$$P_i = \frac{\lambda_{ijk}}{\lambda_{jk}}, \tag{3-4}$$

where λ_{jk} is defined by Equation (3-3).

As each aircraft is generated, a simulated random process using the probabilities p_i is employed to assign a destination to each aircraft. This method assures that aircraft will not be created with destination airports that are shut down because of time of day, since, for times of day when an airport is closed, $\lambda_{jk}=0$. As in Section 3.3.2.1, all the data for this calculation were not available. Appendix A provides details on how destination data for model demonstration were provided.

3.3.2.3 Aircraft Type

A destination having been assigned, the next requirement is to identify the aircraft by type, i.e., air carrier, air taxi, general aviation, or military. The levels of operations at the primary and secondary airports in the Boston TCA can be determined and used in assigning aircraft types. Some of the requisite information has been published. It appears in *FAA Air Traffic Activity, Calendar Year 1975*. This document, dated March 1976, was published by the FAA Office of Management Systems. Table 14 of this analysis, for example, identifies the number of instrument approaches handled by FAA-operated approach control facilities, RAPCONs, and RATCCs -- specifically by the Boston, Otis AFB, and Worcester primary airports and their associated secondary airports. In order to illustrate the method, this table is reproduced here, in part, as Table 3-1.

Table 3-1. NUMBER OF INSTRUMENT APPROACHES BY DESTINATION AND USER CLASS FOR 1975

Airport	Airport Totals	Air Carrier	Air Taxi	General Aviation	Military
Primary Airport (Boston Logan)	26142	20450	3012	2587	93
Secondary Airports					
Bedford	2902	87	235	2425	155
Beverly Municipal	548	0	1	446	101
Fitchburg	38	0	0	38	0
Fort Devens	26	0	0	1	25
Lawrence	200	0	38	162	0
Mansfield	12	0	0	12	0
Marshfield	19	0	0	19	0
Newburyport	1	0	0	1	0
Norwood	1275	2	12	1094	167
Plymouth	15	0	0	15	0
South Weymouth	69	0	0	12	57
Taunton	19	0	0	19	0
Tewkesbury	17	0	4	13	0
Area Totals	31283	20530	3302	6844	598

If it is assumed that an aircraft's destination is Logan and that IFR conditions prevail, the probability that an aircraft is an air carrier is obtained by dividing the number of air carriers going to Logan by the total number of aircraft going to Logan. From the data in the table, it can be seen that

$$P\left[AC|L\right] = \frac{20450}{26142} = 0.78227, \tag{3-5}$$

where

$P\left[AC|L\right]$ = probability that aircraft is an air carrier, given that it is going to Logan.

This procedure is repeated for all airports to obtain the probabilities associated with each aircraft type. These probabilities are accumulated, and a decision is made to assign the type of aircraft on the basis of a random number.

3.3.2.4 Aircraft Origin

Aircraft proceeding to secondary airports are assumed to appear at the airport ready to land. The only question is whether or not they can, depending on facility status and weather conditions. On the other hand, aircraft destined for Logan appear at one of the five holding fixes that serve Logan -- Manjo, Millis, Bridgewater, Skipper, or Lawrence. For purposes of the model configuration, these holding fixes are the origin of aircraft bound for Logan. These assignments are based on a frequency distribution characteristic of origins of flights feeding through these points -- 30 percent to Millis and Manjo, 25 percent to Bridgewater, 5 percent to Skipper, and 10 percent to Lawrence.

3.3.2.5 Aircraft Weight, Category, and Speed

With knowledge of the type of aircraft, three other pieces of information are required: the weight class, the aircraft approach category, and speed. The weight class is required to determine separation criteria in the final approach. The approach category is required to determine landing minima.

A small aircraft, designated S, is an aircraft whose maximum certified takeoff weight is 12,500 pounds or less. A large aircraft, L, weighs more than 12,500 pounds and no more than 300,000 pounds. A heavy aircraft, H, weighs more than 300,000 pounds.*

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*Aircraft weight classes are defined in Chapter 1 of the manual *Air Traffic Control,* 7110.65, 1 January 1976, DOT, FAA, Air Traffic Service.

Approach category definitions* are tabulated as follows:

A. Landing approach speed less than 91 knots, landing weight less than 30,001 pounds

B. Landing approach speed 91 knots or more but less than 132 knots; landing weight 30,001 pounds or more but less than 60,001 pounds

C. Landing approach speed 121 knots or more but less than 141 knots; landing weight 60,001 pounds or more but less than 150,001 pounds

D. Landing approach speed 141 knots or more but less than 166 knots; landing weight 150,001 pounds or more.

Category E aircraft, those aircraft with landing approach speeds greater than 166 knots, are not considered.

Both weight class and approach category are treated as a function of aircraft type. The model assigns aircraft weight class and approach category through two separate random processes. Although there could theoretically be a high correlation between these two factors, the actual mix of aircraft is such that there is little need to correlate the weight class and approach category selection. For example, all general aviation aircraft in the available Logan data base were both small and approach category A. The only problem concerned commercial aircraft, wherein some heavy aircraft could be erroneously assigned to approach category C. However, a model refinement in this one area did not seem to be warranted.

With weight and approach category decided, an approach speed is all that remains to be assigned. The speed is selected on the basis of a uniform speed distribution applicable to the various approach categories:

Category	Speed (knots)	Distribution Range (Knots)
A	71-90	20
B	91-120	30
C	121-140	20
D	141-165	25

The model also simulates aircraft departures, but only those from Logan. It is assumed that the same numbers of aircraft, by type, weight, and approach category, land and take off, although not necessarily on the same schedule. Determination of departure time is accomplished by assigning each aircraft landing at Logan a takeoff time equal to its landing time plus a nominal layover time plus or minus a uniform random variable. Departing aircraft appear at the head of a departing runway, queueing on a first-in/first-out basis.

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*Landing approach categories are defined in *Instrument Approach Procedures* (charts), published by the National Ocean Survey.

3.3.3 Aircraft Control Module

3.3.3.1 Air Traffic Control

Figure 3-5 depicts the air traffic control module.

As described previously, when an aircraft bound for Logan is generated, it is assigned to one of the five inbound holding fixes, where it is held until it can be accepted by a controller for vectors to an approach. A central assumption of this model is that three factors primarily affect delays:

The number of aircraft a controller can handle at one time

The longitudinal, or trail, separation of aircraft in final approach

Whether or not an approach can be made.

The number of aircraft per controller is determined by:

A controller's innate capability and training

Accuracy and information rate of the radar.

Interviews with personnel in Boston TRACON showed that while the capabilities of controllers varied considerably, an average controller, working with the ASR, ARTS-III, and SECRA all operable, could handle ten aircraft between the holding fixes and the point where the aircraft are handed over to the tower control. These same interviews revealed that as the several radars became inoperable (the Winthrop ARSR is included because its raw video can be displayed in the TRACON), the number of aircraft per controller diminished. The last column in Table 3-2 displays nominal numbers of aircraft per controller, as a function of the radar facility environment. To illustrate, suppose the ASR is down, the SECRA is up, the ARTS-III is down, and the Winthrop ARSR is down. The SECRA (beacon radar) is the only radar information available, and the number of aircraft per controller is reduced from a nominal, or average, value of ten to eight.

The manner in which the maximum number of aircraft per controller (MAPC) affects delay is readily seen. Assume that a controller is moving aircraft from a holding fix to a runway and that the runway acceptance rate is unlimited. If the distance from the fix to the runway is D and the aircraft speeds are S, define MAPC as the maximum number of aircraft per controller and NAPH as the number of aircraft moved per hour. If the aircraft the controller handles are assumed equally distant from one another, then this distance is D/MAPC. If the aircraft speed is divided by this quantity, the number of aircraft per hour that the controller can move to the runway, NAPH, is given; that is,

$$\mathrm{NAPH} = \frac{S}{D/\mathrm{MAPC}} = \frac{(\mathrm{MAPC})(S)}{D} . \tag{3-6}$$

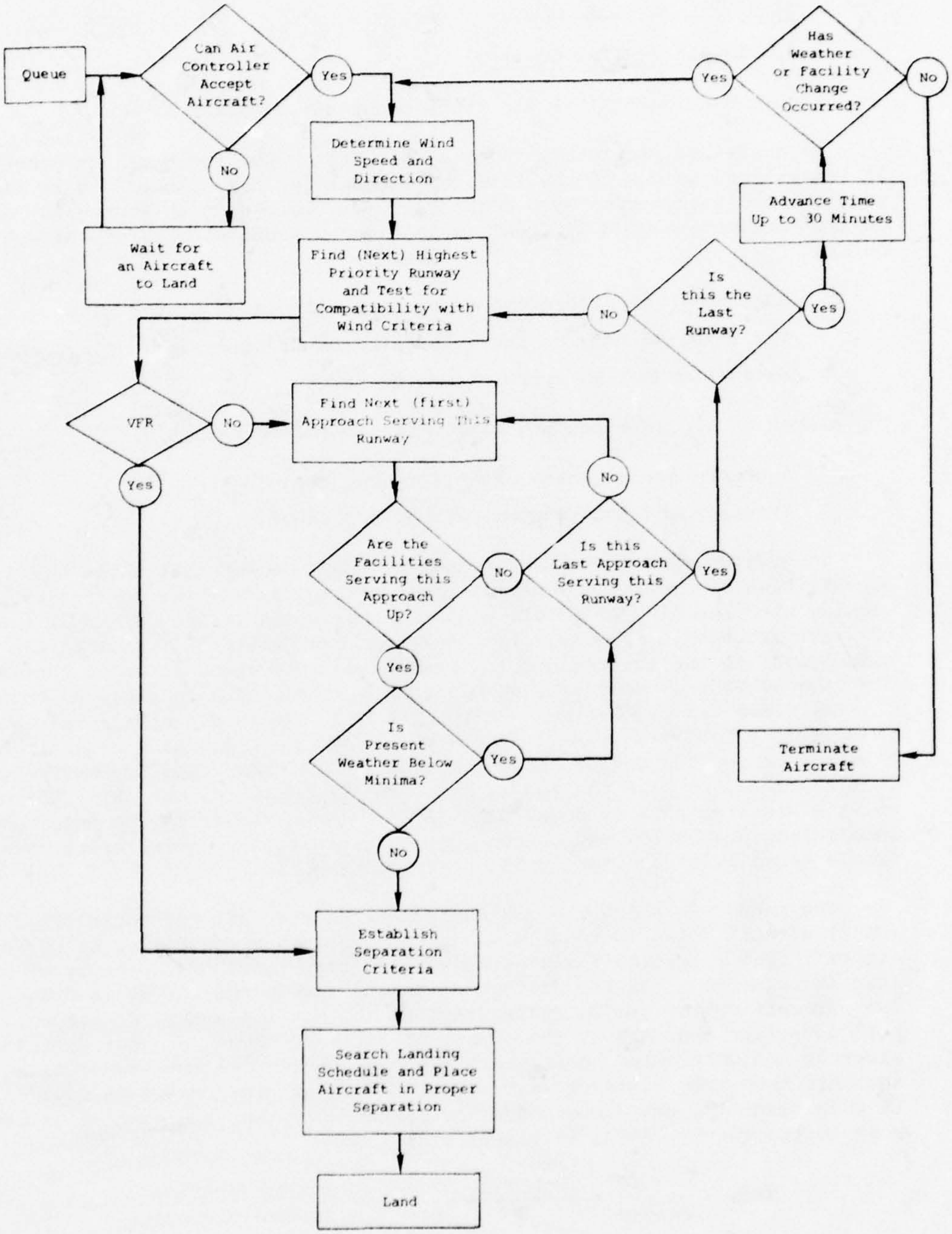


Figure 3-5. AIR TRAFFIC CONTROL MODULE

Table 3-2. AIRCRAFT SEPARATION TABLE

Row Number	Facility Status				Trail Separation Standards (Nautical Miles)						Number of Aircraft per Controller
	ASR	SECRA	ARTS-III	ARSR	Nominal Separation (I)	Differentials (Add to Nominal Separation)*					
						H,H** (II)	L,H** (III)	S,H** (IV)	L,L** (V)	S,L** (VI)	
1	Up	Up	Up	Up	3	1	2	3	0	1	10
2				Down	3	1	2	3	0	1	10
3			Down	Up	3	1	2	3	0	1	8
4				Down	3	1	2	3	0	1	8
5		Down	Up	Up	4	0	1	2	0	0	6
6				Down	4	0	1	2	0	0	6
7			Down	Up	4	0	1	2	0	0	6
8				Down	4	0	1	2	0	0	6
9	Down	Up	Up	Up	3	1	2	3	0	1	10
10				Down	3	1	2	3	0	1	10
11			Down	Up	5	0	0	1	0	0	8
12				Down	5	0	0	1	0	0	8
13		Down	Up	Up	5	0	0	1	0	0	5
14				Down	12	0	0	0	0	0	4
15			Down	Up	5	0	0	1	0	0	5
16				Down	12	0	0	0	0	0	4

*See Paragraph 1420, Air Traffic Control, 1770.65, 1 January 1976, FAA, Air Traffic Service.

**H,H means a heavy aircraft following a heavy; L,H means a large aircraft following a heavy, etc.

For given values of S and D, the rate of removing aircraft from the holding fixes is a linear function of MAPC. If a controller is receiving aircraft from more than one holding fix, then the rate at which he can remove aircraft from any one of these (assuming they are equidistant from the runway) is NAPH/N, where N is the number of holding fixes. If this rate is less than the rate at which aircraft are arriving at these fixes, then queues or stacks will develop. The longer the queues, the greater will be the delay. If the runway acceptance rate if finite and if NAPH is greater than the runway acceptance rate, then, of course, the runway acceptance rate becomes the limiting factor.

The runway acceptance rate is controlled primarily by:

Trail separation in final approach

Runway clearance rate.

Trail separation in final approach, the only one of these two factors allowed to vary in the model, is controlled by several factors, among which are:

Accuracy of navigation

Precision and information rate of the radar

Separation required for wake-vortex avoidance

Runway clearance time.

Table 3-2 is also used by the model to determine separation. A nominal separation is given in column I as a function of radar status. If all radars are up, a nominal separation of 3 nautical miles is provided. Other radar outage combinations give different nominal separations up to a maximum of 5 nautical miles. In the event that all radars are down, radar vectors cannot be provided and the model acts as if any approach to Logan must be made on the Boston VORTAC. In this event, a nominal separation of 12 miles is called for. This is an approximation; it is understood that the actual separation in this case would be achieved by not clearing a following aircraft from a holding fix until the one ahead reports at some prescribed fix. The distance between the two aircraft would therefore be a variable dependent on the holding fix involved and the particular runway in use. The 12-nautical-mile separation is thought, however, to be an adequate approximation.

Columns II through VI of Table 3-2 are incremental separations that are added to the nominal separation determined by column I to provide wake-turbulence avoidance. For example, in the top row, with all radar equipment up, column IV represents a small aircraft following a heavy, and an additional 3-nautical-mile separation is provided, giving a total separation of 6 nautical miles.

The model utilizes the separation-table data to establish the landing sequence. How this sequencing is established is a key aspect of the model, as will be shown in Section 3.3.3.2. As mentioned earlier, in the description of the aircraft generation module, aircraft bound for Logan are placed at one of the five peripheral holding fixes for the purpose of determining the distance from the fix to Logan. It is not necessary, however, to establish five different queues in the model in order to simulate their handling. A single, first-in/first-out (FIFO) queue suffices. This reflects the fact that the two approach controllers are in communication with one another and coordinate their activity so that all aircraft handed off to them are allowed to proceed in approximately their order of appearance.

3.3.3.2 Runway Selection and Landing Sequencing

Before a simulated aircraft is released from the queue that represents the holding fixes, the following steps are taken:

A runway is assigned, taking into account wind speed and direction, types of approach available, weather conditions, and facilities status.

When a runway is found, the distance to that runway from the assigned holding point is found in the distance table and, by use of the aircraft speed, a time of flight is calculated.

By summing the time of flight and present time, an ETA is found. This ETA is used to determine where the aircraft is placed in the landing sequence.

Runway selection is based on the current wind direction and speed coupled with a priority system. It also takes into account the status of facilities that define the several approaches available, the ceiling and visibility conditions, and landing minima. At Logan, the following landing runway priority system is used:

Priority	Day	Night
1	4R/L	33L
2	27-22L	4R
3	33R/L	22L
4	15R/L	

The model first makes a tentative runway selection by taking into account this priority system and wind constraints. It then determines whether or not a landing can actually be made on this runway under prevailing weather conditions and approach availability.

If the wind is 5 knots or less, it is assumed that the wind is calm, as is done at Logan. In this case the highest-priority runway is noted and a check is made, approach by approach, to determine if the facilities necessary for that approach are in an up status. As available approaches are found for the runway under consideration, the minima corresponding to each approach are examined. If the minima are lower than the prevailing ceiling and visibility conditions for that particular runway-approach combination, a viable approach exists and it is assumed that a landing can be made. If the first approach is not viable, the second is checked, and this cycle is continued until a viable approach is found or all approaches for that runway are exhausted. In this case, the next-lower-priority runway is examined. If no viable approach on any runway can be found, the aircraft is delayed at the holding fix until either a viable approach becomes available or 30 minutes have elapsed, at which time the aircraft is presumed to divert to its alternate.

If the wind is greater than 5 knots and is 15 knots or less, the highest-priority runway having the wind direction within ±80 of its direction is selected and tested for the availability of a viable approach. If no viable approach exists on this runway, the next-highest-priority runway is examined, etc., until either a viable approach is found or the aircraft is forced to wait for a weather or facility status change to take place, as above.

When the wind is greater than 15 knots, the runway priority is not considered. The model cycles through each runway, searching for a viable approach, if one or more runways are found having a viable approach, the runway closest to the wind is chosen, regardless of wind direction and speed. Of course, if no viable approaches are available, the aircraft, as before, stays at the holding fix.

All of these checks are made before the aircraft is released from the holding fix. When a runway and approach have been found, a distance table is entered. This table contains the distances in nautical miles from all five holding fixes to all the runways at Logan. The data were taken by direct measurement from the Boston (Logan International), Mass., ASR-7 60-nautical-mile video map prepared by the National Ocean Survey, revised 4 February 1976. The routes were laid out in conformity with the Boston Tower Standard Operating Procedures, dated 15 March 1976, BOS TWR 7110.35. It is understood that these routes vary in length from approach to approach, but the tabulated distances are believed to be representative.

When the distance is found, a time of flight is calculated. In calculating the time of flight, the model increases the landing speed by some factor greater than 1; e.g., in the delivered version of the UDCM, time of flight is set equal to the distance divided by the landing speed doubled. This time of flight is added to the present time to obtain an ETA.

Assuming that there are aircraft ahead of the one being considered, there is a landing schedule that contains the landing time, speed, and weight class of the aircraft already en route to land. The ETA of the present aircraft is compared with those of the aircraft on the landing schedule. When the aircraft just ahead (the lead aircraft, with a landing time just less than this ETA) is found, the required separation between the two aircraft is looked up (see Table 3-2) and a calculation is made, using the two aircraft's speeds, to determine if the ETA will allow proper separation. If it does, then a similar calculation is made for the next, or trail, aircraft on the landing schedule. If separation is assured, the ETA is assigned as the landing time and the aircraft is released from the holding fix. Once an aircraft is released, it will be assumed to land regardless of any subsequent changes in weather or facilities. If it does not clear the lead aircraft, a delay is calculated to assure separation, and a check is made on the trailing aircraft, using the ETA plus the calculated delay. If separation is assured, the landing time is the ETA plus this delay. If separation for the trail aircraft is not assured, it is then treated as the lead aircraft and the cycle is continued until a landing time is found. The difference between the landing time and the ETA is the delay time due to spacing. When a delay is necessary, the aircraft is not automatically released from the holding fix at the termination of the delay, but the whole cycle is repeated to ensure that no weather or facility changes have taken place and that the landing schedule has not changed. If the originally determined conditions continue to prevail, the aircraft is released at the end of its delay time and is assumed to land.

If a viable landing runway cannot be found, aircraft are held for up to 30 minutes, during which time the weather may change or facilities may be restored to service, which will allow landings to be made. If no landing is possible within 30 minutes, the aircraft is scrubbed, as if it were going to an alternate airport. Aircraft bound for secondary airports that cannot land are either scrubbed, as if they are going to another secondary airport, or they are diverted to Logan. An aribtrary proportion, one-half in the present model, are assigned to Logan. For those which are diverted to Logan, a distance table is entered to enable calculation of a time of flight. They are put on the landing schedule in the usual way, with one exception: they are assigned a higher priority than other inbound aircraft. This has the effect of putting them ahead of aircraft waiting to be released from the holding fixes.

At Logan, several different situations are encountered in the assignment of runways for takeoff and landing. These assignments are based on wind conditions and states of the weather. For example, if the wind is less than 15 knots and the weather is VFR, landings are permitted on certain runways intersecting the primary, or preferred, runway. Under these conditions the model sets up another landing schedule to which it assigns small aircraft, and the assumption is made that they land on schedule, with separation at the intersection being maintained by the tower. It is also assumed that when the wind is less than 15 knots, landings and takeoffs are scheduled on different runways and collision is avoided on the landing and takeoff runway intersections by tower action. On the other hand, when the wind is greater than 15 knots, landing and takeoffs will be taking place only on the primary runway, and all landings occur on the primary runway.

If the landing and takeoff runways are different, departing aircraft will be allowed to depart as soon as the first landing aircraft lands, unless the first landing aircraft is two miles or more out in final approach. In this case, the departing aircraft will be allowed to take off ahead of it, given proper separation from any aircraft taking off. In a nonradar (VORTAC only) environment, three-minute separation will be simulated.

If landings and takeoffs are occurring on the same runway, when the wind speed is greater than fifteen knots, the model will simulate a one-minute roll-out and runway clearance time for landing aircraft; i.e., departures will be permitted one minute after prior landing if the next landing aircraft is two or more miles out at runway clearance time. Aircraft taking off are assumed to be handed off to ARTCC immediately. Takeoff is not permitted if the ceiling is less than 375 feet and visibility is less than 1 mile.

When three or more aircraft are in the takeoff queue, aircraft coming off the holding fix will go to five-miles separation or more in final.

3.4 DATA REQUIRED TO EXERCISE THE MODEL

A key element in any simulation model is the input data base. The input data must be complete enough to reflect the elements being simulated, and they must be accurate if the model is to have predictive value. This section will identify the nature of the data necessary to exercise the UDCM. Appendix A discusses and explains the data in greater detail, as well as the methods used to collect it and prepare it for program input. The program documentation, published separately, displays all of the input data matrices with specific numerical values used during model demonstration. The input data required by the model fall into the following categories:

Weather data

Arrival rate as function of:

- Weather, VFR or IFR
- Destination airport
- Time of day

Distribution of aircraft types (air carrier, air taxi, general aviation, military) as a function of weather (VFR, IFR) and destination

Distribution of weight class as a function of type

Distribution of approach category as a function of type

Turnaround time as a function of type

Distribution of holding-fix assignment, e.g., percentage of Logan-bound aircraft coming in over each of the five holding fixes

Distances from holding fixes to the primary airport under radar and nonradar (VORTAC) environment, by runway

Distances from secondary airports to the primary airport by primary airport runway

Minima for each approach serving each runway, by approach category

Identity of all facilities necessary for each approach at each runway

MTBF and MTTR of each facility for the Facility Status File

Trail separations required in landing as a function of radar/VORTAC outage and leading/following aircraft weight classes, and maximum number of aircraft per controller as a function of radar outage

Airport description data.

3.5 MODEL OUTPUTS

The program produces and prints out three kinds of data:

Output data of the run, i.e., delay data of various kinds

Program administrative data

Current values of program parameters.

The program administrative data and current values of program parameters are technical in nature and their discussion is presented in the program documentation, published separately. The run delay data are defined in this section and are discussed at greater length in Chapter Four, the description of the model demonstration.

Run delay output are presented in the form of a computer-printed matrix, an annotated example of which is shown in Figure 3-6. This matrix gives an overall synopsis of the model's operation. The four columns in this matrix signify aircraft type. Column 1 represents air carriers, Column 2 air taxis, Column 3 general aviation, and Column 4 military aircraft. The delay statistics are presented in the matrix by row:

Row 1 - Number of aircraft created at holding fixes and secondary airports

Row 2 - Number of aircraft originally scheduled to the primary airport through the holding fixes

Row 3 - Number of aircraft diverted from secondary airport to primary airport

Row 4 - Time of flight accumulated by secondary-airport aircraft diverted to the primary airport

Row 5 - Number of aircraft landing at primary airport that experience delay

Row 6 - Total delay of landing aircraft [delay = landing time - (creation time + time of flight)]

```
MATRIX HALFWORD SAVEVALUEDELAY

            COL. 1      2      3      4

ROW   1        515     64    160     12
      2        514     56     87      8
      3          0      0     21      4
      4          0      0    462     83
      5        356     33     60      4
      6       7419    801   1418     91
      7       4694    629    968     49
      8         51      9      6      2
      9        462     47     81      6
     10        346     29     56      2
     11       1252     80    153      2
     12         39      2      4      0
     13        461     44     81      2
```

See accompanying explanation of rows

Aircraft Type

1. Number of aircraft created at holding fixes and secondary airports
2. Number of aircraft originally scheduled to the primary airport through the holding fixes
3. Number of aircraft diverted from secondary airport to primary airport
4. Time of flight accumulated by secondary-airport aircraft diverted to the primary airport
5. Number of aircraft landing at primary airport that experienced delay
6. Total delay of landing aircraft
7. Total delay accumulated, for both landing and diverting aircraft, due to separation criteria
8. Number of aircraft not able to land at primary airport and diverted
9. Number of aircraft that landed at primary airport
10. Number of aircraft that experienced takeoff delay at primary airport
11. Total takeoff delay time
12. Total takeoff delay time experienced by aircraft at head of takeoff queue waiting to achieve separation on aircraft taking off ahead
13. Number of aircraft entering the takeoff queue

Figure 3-6. OUTPUT DELAY MATRIX

Row 7 - Total delay accumulated, for both landing and diverting aircraft, due to separation criteria

Row 8 - Number of aircraft not able to land at primary airport and diverted

Row 9 - Number of aircraft that landed at primary airport

Row 10 - Number of aircraft that experienced takeoff delay at primary airport

Row 11 - Total takeoff delay time (the sum of takeoff delay time for aircraft in row 10)

Row 12 - Total takeoff delay time experienced by aircraft at head of takeoff queue waiting to achieve separation on aircraft taking off ahead

Row 13 - Number of aircraft entering the takeoff queue.

These outputs may be called for whenever a user requires them (i.e., every time an aircraft lands, every time 100 aircraft land, every hour, every minute, etc.). When the outputs are printed periodically, they will be cumulative from the time of run commencement.

3.6 MODEL LIMITATIONS

The model has several limitations, some minor, some larger in scope. The development effort was subject to constraints on time and money. The model development began with an identification of the possible features that could be included in the model. Then the time and budget constraints were used in formulating the required model limitations and basic assumptions. To illustrate the sort of questions considered, the issue of incorporating collision-avoidance logic in the route network was examined. Conversations with TSC personnel and persons in the academic community indicated that this would be a very extensive and unnecessary undertaking; it was therefore abandoned in favor of a simpler concept, namely, that "the aircraft will be assumed to be separated by the controller".

Another question was whether or not to simulate traffic through the TCA, understood to be a very large burden on the air controller. It was decided, however, that the first order of priority was what happened at Logan and, more particularly, what happened to aircraft landing at Logan. This priority also dictated the decision to assume that aircraft taking off from Logan are simply handed off to the Boston Center, thus disappearing from the model.

Secondary airport operations are dealt with in very simple fashion. The major simplifications are:

Aircraft appear at the airport at time of creation, rather than at the TCA boundary.

Takeoffs are not simulated at all.

The effect of secondary traffic in the Boston Sector on controller capacity is neglected.

The reasons are as explained above. Events at Logan were considered paramount, and time and money for model development were limited. All of these elements can be added to the model incrementally.

The placement of aircraft in the landing schedule does not take into account a system of priorities based on aircraft speed and weight. It is recognized that in practice the controllers do take these factors into account, but in a way that reflects the extreme complexity of the human decision process. Refinement is possible in this area.

There is no provision in the model for the effect of deterioration in the quality of voice radio communications. Quantification of this phenomenon is the subject of a more sophisticated and extensive form of analysis, which has not been undertaken.

An important meteorological phenomenon is the cloud deck between 1000 and 3000 feet. A descent through such a deck must be IFR, and an IFR approach must be made to landing. The model does not recognize this, simply because data relating to the distribution of this condition were not known. The impact of this limitation is that IFR approaches are made less frequently by the model than in reality. Acquiring data for the weather module was a major source of delay in model development. Given more complete weather data, this limitation can be easily overcome.

The model is programmed in General Purpose Simulation System (GPSS) language. The basic cycling interval for the UDCM is one minute. This means that every clock GPSS pulse is interpreted as one minute of simulated real time. The use of a one-minute clock implies an analytical error in calculation because all calculations involving time are integer quantities. For example, any calculation, such as a distance divided by a speed, will truncate downward to the next lower integer so that, say, all times between 4.0 and 4.999 minutes will be interpreted as 4 minutes. Thus the same time of flight would be obtained over a range of distances and/or velocities. Obviously, then, some error is built into the model. This could be reduced by allowing one clock pulse to stand for 0.1 or 0.01 minute, or any other fraction of a minute. Such reduction would, however, increase the model's core constraints, already very tight, since in order to obtain runs of any reasonable simulated duration, the halfword savevalues and matrices would have to be increased to fullword values.

In summary, it is believed that the limitations noted are important but that the model does handle the first-order effects and that, given the modular construction and central logic, second-order effects can easily be incorporated later.

CHAPTER FOUR

UDCM DEMONSTRATION

The purpose of demonstrating the UDCM was to assure that it functions correctly and that it is sensitive to facility outage as well as to aircraft schedule and weather.

The demonstration consisted of ten runs of the model, five conducted at the Transportation Systems Center by ARINC Research personnel during the period 20 through 22 September 1976, and five conducted at ARINC Research from 27 September through 22 October 1976. The runs at ARINC Research were made by using a version of the model with the weather module removed and the weather conditions preset in the program logic. Removal of the weather module conserved computer core, expedited the runs, and made it possible to select a particular weather condition.

The demonstration of the model showed the following:

Strong model sensitivity to aircraft arrival rate

Strong sensitivity to facility outage, when the arrival rate is low enough not to mask the effect

Sensitivity to weather conditions.

In the following sections all model runs will be explained and analyzed.

4.1 RUN DESCRIPTIONS

Tables 4-1 and 4-2 describe the run scenarios. The primary difference between the two sets of runs was the overall aircraft arrival rate. The arrival rate, 1887 per day in set 1, was reduced in later demonstration runs to investigate the effect of varying this factor.

In both sets a baseline run was made with all radar facilities "up". These are runs 1 and 6. Variations of facility outages in the first five runs were made on the basis of suggestions by TSC personnel. In the second set of five runs, it was decided to investigate the effects not only of facility outage but of the other factors as well, i.e., schedule and weather.

Table 4-1. UDCM DEMONSTRATION RUN DESCRIPTIONS, 21-22 SEPTEMBER 1976

Run Number	Facility Status	Weather	Number of Aircraft Generated
1	ASR, ARTS, ARSR, SECRA up; other random	Random, VFR probably	1887
2	ARTS and SECRA down 24 hours; others random	Same	1887
3	ASR, ARTS, ARSR, SECRA down from 5-7 P.M.; others random	Same	1887
4	ARTS, SECRA down from 5-7 P.M.; others random	Same	1887
5	ASR, ARTS, ARSR, SECRA down 24 hours; others random	Same	1887

Table 4-2. UDCM DEMONSTRATION RUN DESCRIPTIONS, 27 SEPTEMBER - 22 OCTOBER 1976

Run Number	Facility Status	Wind Direction/ Velocity	Ceiling (Feet)	Visibility (Miles)	Number of Aircraft Generated	Aircraft Speed from Holding Fix to Final Approach
6	All up	N/10	1000+	3+	1007	Landing Speed
7	ASR, ARTS, SECRA, ARSR down 24 hours; others up	N/10	1000+	3+	1007	Landing Speed
8	All up	N/10	1000+	3+	1007	2X Landing Speed
9	All up	N/10	1000+	3+	662	2X Landing Speed
10	ASR down 24 hours; others up	N/18	600	1.5	751	2X Landing Speed

As a consequence of this additional variation, a more complete analysis is possible. For example, runs 1 and 6 are identical, all radars up, except that they differ in arrival rate. Similarly, runs 5 and 7 are identical, all radars down for 24 hours, except that they too differ in arrival rate. Hence comparison of these four runs should provide evidence of model sensitivity to arrival rate.

Run 9 is the same as run 8 except that the arrival rate is even lower. The purpose of this run was to observe the effect of a very low arrival rate.

Finally, run 10 was designed to test the runway-selection procedure in the model. The wind was set at 18 knots from the north, and the ASR was placed in a "down" condition. When the wind is greater than 15 knots, the runway closest to the wind should be selected, provided a viable instrument approach exists. If a viable instrument approach cannot be found, the runway next closest to the wind with an instrument approach available should be the one chosen. Runway 33 is closest to north. It has an ASR approach with a 480-foot ceiling minimum. No other approach on runway 33 has a minimum less than the prevailing ceiling of 600 feet and 1.5-mile visibility. The model should therefore select a runway next closest to the wind with an approach available and with minima below prevailing weather. The model did this, with runway 4 (ILS approach) being selected on all landings of the run.

4.2 MEASURES OF DELAY AND MEASURES OF EFFECTIVENESS

The delay measures were described in Section 3.5. For the convenience of the reader, they are repeated in Table 4-3 with amplifying comments. From these basic model outputs, several additional measures of effectiveness can be defined that will be useful in run analysis.

Define:

M1 = line 8 ÷ line 2 = percent diverted from Logan. This measure identifies the grossest form of interruption of service to the using community.

M2 = line 8 × 30 = number of minutes lost by diverting aircraft.

M3 = M2 + line 6 = total delay to aircraft that land and to those which divert.

M4 = M3 ÷ line 2 = minutes delay per aircraft originally scheduled to land at primary airport

M5 = line 7 ÷ (line 8 + line 5) = delay due to spacing per aircraft for aircraft which landed and those diverted. This measure is not precise, since it does not divide total spacing delay by the actual number of aircraft thus delayed (which is not recorded). It does, however, show the average spacing delay of those aircraft which were subject to it.

Table 4-3. EXPLANATION OF DELAY MEASURES

Delay Measure	Comment
1. Number of aircraft created at holding fixes and secondary airports.	This is simply the sum of all aircraft-creation events in the program.
2. Number of aircraft originally scheduled to the primary airport through the holding fixes.	This number is contained in the total shown in line 1.
3. Number of aircraft diverted from secondary airports to primary airport.	When weather is below minimum at secondary airports, 50% divert to Logan. They are assigned a higher priority for air controller pick-up than aircraft at the holding fixes.
4. Time of flight accumulated by secondary-airport aircraft diverted to the primary airport.	A distance table in the program contains the distance from each secondary airport to the primary airport. When a diversion to Logan takes place, the time of flight is calculated. Line 4 is the sum of these times.
5. Number of aircraft landing at primary airport that experienced delay.	Delay is defined as the difference between time of creation plus time of flight and landing time. This line shows the number of aircraft for which this difference was not zero.
6. Total delay of landing aircraft	This is the sum of delay times experienced by aircraft delayed (reported in line 5).
7. Total delay accumulated, for both landing and diverting aircraft, due to separation criteria	The ETA is the sum of the time of acceptance by a controller and the time of flight. If the ETA will not fit the landing schedule, a later scheduled landing time is found. The difference is delay due to spacing. An aircraft may not be able to leave the holding fix at the end of its separation delay; a facility may have gone down in the interim. If it cannot leave the fix within 30 minutes, it diverts. Thus it is possible for both landing and diverting aircraft to accumulate spacing delays.
8. Number of aircraft not able to land at primary airport and diverted	If an aircraft is not released from a holding fix within 30 minutes of its creation time, it is assumed to divert. It is possible for an aircraft previously diverted to Logan from a secondary airport to subsequently be diverted from the primary airport.
9. Number of aircraft that landed at primary airport	This is the total number of aircraft landing at the primary airport. It includes aircraft previously diverted from secondary airports.
10. Number of aircraft that experienced takeoff delay at primary airport	Since takeoffs from secondary airports are not simulated in the model, this measure is applicable only to the primary airport. Delay here is defined as the difference between the time the aircraft enters the takeoff queue and its actual time of departure.
11. Total takeoff delay time	This is the sum of the delay times for all aircraft delayed taking off.
12. Total takeoff delay time experienced by aircraft at head of takeoff queue waiting to achieve separation on aircraft taking off ahead	If an aircraft otherwise ready for takeoff is delayed because the aircraft taking off ahead has not achieved proper time separation (1 minute in radar environment, 3 minutes in non-radar environment), it is delayed until this separation is assured.
13. Number of aircraft entering the takeoff queue	After an aircraft lands at the primary airport, it is assigned a random turnaround time. At this time it enters the takeoff queue. This measure is the total number of aircraft entering this queue. This line was not available for runs 1 through 5.

M6 = line 9 ÷ 24 = average landing rate per hour, over the 24-hour run period.

M7 = line 11 ÷ line 10 = minutes delay per delayed takeoff aircraft.

M8 = M3 + line 11 = total delay to landing, diverting, and taking off aircraft.

M9 = minutes total delay per aircraft scheduled for primary airport, M8 ÷ line 2.

4.3 MODEL DEMONSTRATION OUTPUTS

Tables 4-4 and 4-5 summarize the delay outputs and derived measures of effectiveness for all 10 runs. These two tables provide a concise reference to accompany Sections 4.3.1 through 4.3.10. In these sections the complete run delay outputs and measures of effectiveness are displayed in Tables 4-6 through 4-25. Sections 4.3.1 through 4.3.10 are brief descriptions of run results and provide some basis for comparing results among the runs. An analysis leading to more general conclusions is presented in Section 4.4.

4.3.1 Run 1 (Tables 4-6 and 4-7)

In the discussion of run 1, attention will be given to explaining not only the run itself but the significance of the tables of delay data and the derived measures of effectiveness. This will serve as an introduction to the tables and their use. Subsequent runs will not be addressed to this level of detail.

Table 4-6 shows the 13 delay measures printed out by the model. They are displayed in the same matrix format as they appear in the computer printout, with one exception: a fifth column has been added that contains, for each measure, the totals for all aircraft types (user classes).

The total number of arrivals, i.e., aircraft generated, during the 24-hour simulated run is 1887, or about 67.5 per hour, with peak hourly rates somewhat higher. Of the 1887 created, line 2 shows that 1620 were scheduled for Logan, the rest for secondary airports. This leads to system saturation, with the result that many aircraft cannot land. Line 8, the number diverted from Logan, shows 629 air carriers, 89 air taxis, 65 general aviation, and 2 military, for a total of 788 in this category.

Lines 3 and 4 provide information about aircraft that were scheduled for secondary airports but were unable to land. As mentioned earlier, 50 percent of these are assumed to proceed to Logan. In runs 1 through 5 the weather module was operating; and while no record was kept of the weather conditions that were simulated, it may be surmised that at some time the weather was below minima for one of the secondary airports. It can be seen in line 3 that one general aviation aircraft was sent to Logan from a secondary airport. Line 4 shows the time of flight to Logan for these diverted aircraft that actually land. Since no time of flight is shown, that single diverted general aviation aircraft did not land at Logan, and it can be assumed that it was diverted.

Table 4-4. DELAY OUTPUTS - RUN TOTALS										
Delay Measure	Run Number									
	1	2	3	4	5	6	7	8	9	10
1. Number of Aircraft Created at Holding Fixes and Secondary Airports	1887	1887	1887	1887	1887	1007	1007	1007	642	751
2. Number of Aircraft Originally Scheduled to the Primary Airport Through the Holding Fixes	1620	1620	1620	1620	1620	864	864	864	568	659
3. Number of Aircraft Diverted from Secondary Airport to Primary Airport	1	1	1	1	1	0	0	0	0	25
4. Time of Flight Accumulated by Secondary-Airport Aircraft Diverted to the Primary Airport	0	0	0	0	0	0	0	0	0	545
5. Number of Aircraft Landing at Primary Airport That Experienced Delay	682	507	597	636	255	559	248	568	251	453
6. Total Delay of Landing Aircraft	24293	16151	21061	22036	10847	13274	10587	13748	[illegible]	9729
7. Total Delay Accumulated, for Both Landing and Diverting Aircraft, Due to Separation Criteria	8415	3659	7893	7786	5207	5686	4904	8039	938	6340
8. Number of Aircraft Not Able to Land at Primary Airport and Diverted	788	1040	873	832	1334	99	595	95	0	68
9. Number of Aircraft That Landed at Primary Airport	828	574	743	781	272	762	266	768	567	596
10. Number of Aircraft That Experienced Takeoff Delay at Primary Airport	485	129	413	401	266	380	262	463	200	433
11. Total Takeoff Delay Time	940	162	1210	686	781	751	741	773	284	1487
12. Total Takeoff Delay Time Experienced by Aircraft at Head of Takeoff Queue Waiting to Achieve Separation on Aircraft Taking Off Ahead	0	0	0	0	0	0	0	0	0	45
13. Number of Aircraft Entering the Takeoff Queue	NA	NA	NA	NA	NA	754	262	759	558	

Table 4-5. MEASURES OF EFFECTIVENESS FOR RUN TOTALS

Measure of Effectiveness	Run Number									
	1	2	3	4	5	6	7	8	9	10
M1. Percent Diverted from Logan: (line 8 ÷ line 2) × 100	48.64	64.19	53.89	51.36	82.34	11.46	68.86	10.99	0	10.32
M2. Minutes Lost by Diverting Aircraft: line 8 × 30	23640	31200	26190	24960	40020	2970	17850	2850	0	2040
M3. Total Delay of Delayed Landing and Diverted Aircraft: M2 + line 6	47933	47351	47251	46996	50867	16244	28437	16598	938	11769
M4. Minutes Delay per Aircraft Scheduled for Logan: M3 ÷ line 2	29.59	29.23	29.17	29.01	31.40	18.80	32.91	19.21	1.65	17.86
M5. Minutes Spacing Delay per Aircraft: line 7 ÷ (line 8 + line 5)	5.72	2.36	5.64	5.30	3.28	8.64	5.82	12.12	3.73	12.17
M6. Average Landing Rate, Aircraft per Hour: line 9 ÷ 24	34.5	23.92	30.96	32.54	11.33	31.75	11.08	32.0	23.62	24.83
M7. Minutes Delay per Delayed Takeoff Aircraft: line 11 ÷ line 10	1.94	1.26	2.93	1.71	2.94	1.98	2.83	1.67	1.42	3.43
M8. Minutes Total Delay for Landing, Diverting, and Taking Off Aircraft: M3 + line 11	48873	47513	48461	47682	51648	16995	29178	17371	1222	13256
M9. Minutes Total Delay per Aircraft Scheduled for Logan: M8 ÷ line 2	30.17	29.33	29.91	29.43	31.88	19.67	33.77	20.10	2.15	20.11

Table 4-6. DELAY MATRIX - RUN 1

Run No. 1 Facility Status ASR, SECRA, ARTS, ARSR - Up

WX: ☒ Random ☐ Controlled → Wind Direction ________ Ceiling ________
Wind Speed ________ Visibility ________

Delay Measure	Aircraft Type				
	Air Carrier	Air Taxi	General Aviation	Military	Totals
1. Number of Aircraft Created at Holding Fixes and Secondary Airports	1299	177	375	36	1887
2. Number of Aircraft Originally Scheduled to the Primary Airport Through the Holding Fixes	1295	162	156	7	1620
3. Number of Aircraft Diverted from Secondary Airport to Primary Airport	0	0	1	0	1
4. Time of Flight Accumulated by Secondary-Airport Aircraft Diverted to the Primary Airport	0	0	0	0	0
5. Number of Aircraft Landing at Primary Airport That Experienced Delay	557	57	66	2	682
6. Total Delay of Landing Aircraft	20224	2192	1818	59	24293
7. Total Delay Accumulated, for Both Landing and Diverting Aircraft, Due to Separation Criteria	7622	777	14	2	8415
8. Number of Aircraft Not Able to Land at Primary Airport and Diverted	629	89	65	5	788
9. Number of Aircraft That Landed at Primary Airport	662	73	91	2	828
10. Number of Aircraft That Experienced Takeoff Delay at Primary Airport	405	28	51	1	485
11. Total Takeoff Delay Time	779	51	109	1	940
12. Total Takeoff Delay Time Experienced by Aircraft at Head of Takeoff Queue Waiting to Achieve Separation on Aircraft Taking Off Ahead	0	0	0	0	0
13. Number of Aircraft Entering the Takeoff Queue	NA	NA	NA	NA	NA

Table 4-7. MEASURES OF EFFECTIVENESS - RUN 1

Measure of Effectiveness	Aircraft Type				
	(1) Air Carriers	(2) Air Taxis	(3) General Aviation	(4) Military	(5) Total
M1. Percent Diverted from Logan: (line 8 ÷ line 2) × 100	48.57	54.94	41.67	71.43	48.64
M2. Minutes Lost by Diverting Aircraft: line 8 × 30	18870	2670	1950	150	23640
M3. Total Delay of Delayed Landing and Diverted Aircraft: M2 + line 6	39094	4862	3768	209	47933
M4. Minutes Delay per Aircraft Scheduled for Logan: M3 ÷ line 2	30.19	30.01	24.15	29.86	29.59
M5. Minutes Spacing Delay per Aircraft: line 7 ÷ (line 8 + line 5)	6.43	5.32	0.11	0.28	5.72
M6. Average Landing Rate, Aircraft per Hour: line 9 ÷ 24	27.58	3.04	3.79	0.08	34.5
M7. Minutes Delay per Delayed Takeoff Aircraft: line 11 ÷ line 10	1.92	1.82	2.14	1.0	1.94
M8. Minutes Total Delay for Landing, Diverting, and Taking Off Aircraft: M3 + line 11	39873	4913	3877	2.0	48873
M9. Minutes Total Delay per Aircraft Scheduled for Logan: M8 ÷ line 2	30.79	30.32	24.85	30	30.17

Line 5 shows that a total of 682 aircraft landing at Logan experienced delay from some cause, while line 6 gives the sum of all these delays, in minutes. As mentioned earlier, line 7 shows the total delay minutes attributable to placing aircraft on the landing schedule, as opposed, for example, to delay resulting from controller saturation, facility outage, or weather.

A total of 828 aircraft landed at Logan. Since 1620 were scheduled to Logan, and 828 landed and 788 diverted, there is a deficit of 1620 - 828 - 788 = 4 aircraft unaccounted for. It can be concluded that these aircraft were on the landing schedule when the model run ended.

Of the aircraft which, after landing, took off from Logan, 485 experienced some kind of delay, as shown in line 10. Just as line 6 shows the total delay to aircraft that landed, line 11 displays the total delay in minutes to those taking off. Line 12 shows no delays to lead aircraft in the takeoff queue awaiting separation on aircraft taking off ahead.

As noted earlier, the feature of the model that produces line 13, the number of aircraft entering the takeoff queue, was not in the version of the model exercised in runs 1 through 5. The entry NA means that this datum is not applicable.

The data in Table 4-6 are informative in themselves, and similar data are provided for all ten runs. Even so, the measures of effectiveness defined previously, and others that analysis may call for, are more easily interpreted. Accordingly, Table 4-7 is provided in order to give better insight into model operation.

The first measure, M1, the percentage of aircraft diverted from Logan, is perhaps most revealing. A total of 48.64 percent of the aircraft scheduled for Logan could not land within 30 minutes and were assumed to divert. This effect is due simply to saturation. The principal causes were acceptance rate on the runway, due to trail separation requirements, and limitations of controller capacity. The diverted aircraft, 788, each waited 30 minutes before diverting, for a total of 23,640 minutes. This is shown in M2, column 5.

M3 is the measure of total delay to landing aircraft, plus M2, another measure of delay, and is seen to be 47,933 minutes. If this is divided by the total number of aircraft scheduled for Logan, an average delay of almost 30 minutes is recorded as M4.

M5 is a measure of density of the landing schedule because when there are many aircraft in the landing schedule, there are fewer vacancies close to the runway threshold. It will be noted that for general aviation and military aircraft, this measure tends to be smaller than for the other user classes. The reason is that when the weather is VFR and the wind is less than 15 knots, small aircraft land on a secondary runway. Thus the landing schedule tends to be less crowded. Since the arrival rates for these two user classes are much lower than for the larger aircraft, there tend to be fewer aircraft on the landing schedule, hence less individual delay in entering.

The average landing rate, M6, of 34.5 per hour is indicative of how close the model is to saturation. At 34.5 per hour, this is equivalent to one aircraft every minute and 45 seconds. It has already been noted that in VFR weather with a wind less than 15 knots, landings are taking place simultaneously on the primary and secondary runways. Thus, consider that all users other than general aviation land on the primary runway; then the arrival rate on the primary runway is 30.7 per hour, or one every 1.95 minutes. If an average approach speed of 140 knots is assumed, the average trail separation is 4.56 miles. Considering the wake-vortex incremental additions to the nominal 3-mile separation, the 4.56-mile figure should be close to the theoretical minimum. It is noted that the model does not take into account the fact that in visual conditions, actual separations may be less than nominal and that under these conditions certain actions are available to the pilot and tower controller to reduce wake-vortex separations. Neither does the model account for runway clearance by an aircraft landing ahead of a landing aircraft. In the event that this were desired in the model, one minute would be the minimum runway clearance time (see limitation on GPSS clerk in Section 3.6). A one-minute runway clearance time would not impose a limit on the runway acceptance rate, assuming a 140-knot average landing speed, unless trail separation in final were 2.33 nautical miles or less.

The number of minutes delay per aircraft taking off, M7, is 1.94 minutes.

M8 is another measure of delay. The fact that it is only slightly higher than M3 indicates that takeoff delay is not as serious a problem in high traffic density as that encountered by aircraft attempting to land. M9 also reflects this fact when compared with M4. In other runs with lower traffic density (see runs 9 and 10), takeoff delay is a larger percentage of total delay.

4.3.2 Run 2 (Tables 4-8 and 4-9)

Run 2, with the ARTS and SECRA down for 24 hours, shows an increase in the number of diversions. This is due to the decrease in the numbers of aircraft per controller from 10 to 6. As a consequence, fewer aircraft per hour are accepted; hence fewer land. Table 4-9 shows the overall landing rate reduced from 34.5 in run 1 to 23.92 aircraft per hour. This is also reflected in M5, the average minutes delay due to separation. This is down from 5.72 minutes on run 1 to 2.36 minutes on this run, indicating that because fewer aircraft are landing, once the aircraft is accepted by the controller, the landing queue is less dense and the aircraft can be sequenced into it more quickly. The drop in M7, minutes delay per delayed takeoff aircraft, relative to run 1, reflects the fact that since fewer aircraft are landing, fewer are taking off, and less delay is encountered waiting for separation on landing aircraft.

Table 4-8. DELAY MATRIX - RUN 2

Run No. 2 Facility Status ARTS and SECRA - Down

WX: ☒ Random ☐ Controlled → Wind Direction ________ Ceiling ________

Wind Speed ________ Visibility ________

Delay Measure	Aircraft Type				
	Air Carrier	Air Taxi	General Aviation	Military	Totals
1. Number of Aircraft Created at Holding Fixes and Secondary Airports	1299	177	375	36	1887
2. Number of Aircraft Originally Scheduled to the Primary Airport Through the Holding Fixes	1295	162	156	7	1620
3. Number of Aircraft Diverted from Secondary Airport to Primary Airport	0	0	1	0	1
4. Time of Flight Accumulated by Secondary-Airport Aircraft Diverted to the Primary Airport	0	0	0	0	0
5. Number of Aircraft Landing at Primary Airport That Experienced Delay	403	45	56	3	507
6. Total Delay of Landing Aircraft	13187	1461	1411	92	16151
7. Total Delay Accumulated, for Both Landing and Diverting Aircraft, Due to Separation Criteria	3299	336	22	2	3659
8. Number of Aircraft Not Able to Land at Primary Airport and Diverted	837	109	90	4	1040
9. Number of Aircraft That Landed at Primary Airport	452	53	66	3	574
10. Number of Aircraft That Experienced Takeoff Delay at Primary Airport	107	8	12	2	129
11. Total Takeoff Delay Time	133	9	17	3	162
12. Total Takeoff Delay Time Experienced by Aircraft at Head of Takeoff Queue Waiting to Achieve Separation on Aircraft Taking Off Ahead	0	0	0	0	0
13. Number of Aircraft Entering the Takeoff Queue	NA	NA	NA	NA	NA

Table 4-9. MEASURES OF EFFECTIVENESS - RUN 2

Measure of Effectiveness	Aircraft Type				
	(1) Air Carriers	(2) Air Taxis	(3) General Aviation	(4) Military	(5) Total
M1. Percent Diverted from Logan: (line 8 ÷ line 2) × 100	64.63	67.28	57.69	57.14	64.19
M2. Minutes Lost by Diverting Aircraft: line 8 × 30	25110	3270	2700	120	31200
M3. Total Delay of Delayed Landing and Diverted Aircraft: M2 + line 6	38297	4731	4111	212	47351
M4. Minutes Delay per Aircraft Scheduled for Logan: M3 ÷ line 2	29.57	29.20	26.35	30.29	29.23
M5. Minutes Spacing Delay per Aircraft: line 7 ÷ (line 8 + line 5)	2.66	2.18	0.15	0.29	2.36
M6. Average Landing Rate, Aircraft per Hour: line 9 ÷ 24	18.83	2.21	2.75	0.125	23.92
M7. Minutes Delay per Delayed Takeoff Aircraft: line 11 ÷ line 10	1.24	1.125	1.42	1.5	1.26
M8. Minutes Total Delay for Landing, Diverting, and Taking Off Aircraft: M3 + line 11	38430	4740	4128	2.5	47513
M9. Minutes Total Delay per Aircraft Scheduled for Logan: M8 ÷ line 2	29.68	29.20	26.46	30.71	29.33

The fact that fewer aircraft were delayed relative to run 1, line 5 in Table 4-8, can be misleading since this figure reflects only delays to aircraft that actually landed; M4, minutes delay per aircraft scheduled to Logan, includes both landing delays and diversions and would be a better measure. Its decrease from 29.59 to 29.23 is not statistically significant. It should also be noted that the assignment of a 30-minute delay to a diverted aircraft is not an adequate measure of the ultimate delay and cost of diverting. The sharp increase in the number of diverted aircraft, from 788 to 1040, should be considered the primary measure in the comparison of runs 1 and 2.

4.3.3 Run 3 (Tables 4-10 and 4-11)

Run 3 was made with the principal TRACON facilities out from 5 to 7 P.M., which were hours of heavy traffic. The results of this run do not look significantly different from those of run 2. It can be seen that the number of diversions did increase from 507 in run 2 to 597, reflecting the use of the VORTAC approach during the busy hours.

4.3.4 Run 4 (Tables 4-12 and 4-13)

In run 4 the ARTS and SECRA are down from 5 to 7 P.M. The effect was to leave nominal trail separation at 3 miles and decrease controller capacity from 10 to 8. Considering that these restrictions were in effect only for 2 hours, the results would not be expected to differ from those of run 1. No significant differences are noted.

4.3.5 Run 5 (Tables 4-14 and 4-15)

Run 5 is the "worst case" for this series of runs. The number delayed in landing is sharply down, but the number diverted is up to 1334, out of 1620 scheduled into Logan. M6, the landing rate, is down to 11.33 aircraft per hour. For aircraft landing on the primary runway, 201 air carriers plus 26 air taxis and 2 military, this works out to 12.75 miles, on the average, in trail separation, a figure compatible with the 12-mile separation required for VORTAC approaches.

4.3.6 Run 6 (Tables 4-16 and 4-17)

Run 6 is the first of the second series of runs. This is the "baseline" run with all facilities operating. The only essential difference between this run and run 1 is in the lower rate of aircraft generation. An average of 36 per hour are scheduled to Logan. The peak generation rate used in the rate input data was 60 per hour from 4:00 P.M. to 5:00 P.M. The most marked result is the sharp drop in the number diverted, from 788 in run 1 to 99 in this run. The minutes spacing delay per aircraft, M5, is up, indicating a dense landing schedule. M4, delay per delayed aircraft, is down by about 11 minutes from the first 5 runs, while M9, total delay per aircraft scheduled for Logan, is down from about 30 minutes for the earlier runs to 19.67 minutes. This run shows a definite model responsiveness to the level of scheduled activity.

Table 4-10. DELAY MATRIX - RUN 3

Run No. 3 Facility Status ASR, ARTS, ARSR, SECRA - Down 5-7 P.M.

WX: ☒ Random ☐ Controlled → Wind Direction ________ Ceiling ________
Wind Speed ________ Visibility ________

Delay Measure	Aircraft Type				
	Air Carrier	Air Taxi	General Aviation	Military	Totals
1. Number of Aircraft Created at Holding Fixes and Secondary Airports	1299	177	375	36	1887
2. Number of Aircraft Originally Scheduled to the Primary Airport Through the Holding Fixes	1295	162	156	7	1620
3. Number of Aircraft Diverted from Secondary Airport to Primary Airport	0	0	1	0	1
4. Time of Flight Accumulated by Secondary-Airport Aircraft Diverted to the Primary Airport	0	0	0	0	0
5. Number of Aircraft Landing at Primary Airport That Experienced Delay	491	51	52	3	597
6. Total Delay of Landing Aircraft	17614	1927	1404	116	21061
7. Total Delay Accumulated, for Both Landing and Diverting Aircraft, Due to Separation Criteria	7171	684	9	29	7893
8. Number of Aircraft Not Able to Land at Primary Airport and Diverted	695	95	79	4	873
9. Number of Aircraft That Landed at Primary Airport	596	67	77	3	743
10. Number of Aircraft That Experienced Takeoff Delay at Primary Airport	347	28	37	1	413
11. Total Takeoff Delay Time	958	148	88	16	1210
12. Total Takeoff Delay Time Experienced by Aircraft at Head of Takeoff Queue Waiting to Achieve Separation on Aircraft Taking Off Ahead	0	0	0	0	0
13. Number of Aircraft Entering the Takeoff Queue	NA	NA	NA	NA	NA

Table 4-11. MEASURES OF EFFECTIVENESS - RUN 3

Measure of Effectiveness	Aircraft Type				
	(1) Air Carriers	(2) Air Taxis	(3) General Aviation	(4) Military	(5) Total
M1. Percent Diverted from Logan: (line 8 ÷ line 2) × 100	53.67	58.64	50.64	57.14	53.89
M2. Minutes Lost by Diverting Aircraft: line 8 × 30	20850	2850	2370	120	26190
M3. Total Delay of Delayed Landing and Diverted Aircraft: M2 + line 6	38464	4777	3774	236	47251
M4. Minutes Delay per Aircraft Scheduled for Logan: M3 ÷ line 2	29.70	29.49	24.19	33.71	29.17
M5. Minutes Spacing Delay per Aircraft: line 7 ÷ (line 8 + line 5)	6.05	4.68	0.07	4.14	5.64
M6. Average Landing Rate, Aircraft per Hour: line 9 ÷ 24	24.83	2.79	3.21	0.125	30.96
M7. Minutes Delay per Delayed Takeoff Aircraft: line 11 ÷ line 10	2.76	5.28	2.38	16.0	2.93
M8. Minutes Total Delay for Landing, Diverting, and Taking Off Aircraft: M3 + line 11	39422	4925	3862	252	48461
M9. Minutes Total Delay per Aircraft Scheduled for Logan: M8 ÷ line 2	30.44	30.40	24.76	36.0	29.91

Table 4-12. DELAY MATRIX - RUN 4

Run No. 4 Facility Status ARTS, SECRA - Down 5-7 P.M.

WX: ☒ Random ☐ Controlled → Wind Direction ________ Ceiling ________
Wind Speed ________ Visibility ________

Delay Measure	Aircraft Type				
	Air Carrier	Air Taxi	General Aviation	Military	Totals
1. Number of Aircraft Created at Holding Fixes and Secondary Airports	1299	177	375	36	1887
2. Number of Aircraft Originally Scheduled to the Primary Airport Through the Holding Fixes	1295	162	156	7	1620
3. Number of Aircraft Diverted from Secondary Airport to Primary Airport	0	0	1	0	1
4. Time of Flight Accumulated by Secondary-Airport Aircraft Diverted to the Primary Airport	0	0	0	0	0
5. Number of Aircraft Landing at Primary Airport That Experienced Delay	515	55	61	5	636
6. Total Delay of Landing Aircraft	18224	2047	1676	89	22036
7. Total Delay Accumulated, for Both Landing and Diverting Aircraft, Due to Separation Criteria	7078	691	15	2	7786
8. Number of Aircraft Not Able to Land at Primary Airport and Diverted	671	91	70	4	832
9. Number of Aircraft That Landed at Primary Airport	620	71	87	3	781
10. Number of Aircraft That Experienced Takeoff Delay at Primary Airport	341	22	38	0	401
11. Total Takeoff Delay Time	588	36	62	0	686
12. Total Takeoff Delay Time Experienced by Aircraft at Head of Takeoff Queue Waiting to Achieve Separation on Aircraft Taking Off Ahead	0	0	0	0	0
13. Number of Aircraft Entering the Takeoff Queue	NA	NA	NA	NA	NA

Table 4-13. MEASURES OF EFFECTIVENESS - RUN 4

Measure of Effectiveness	Aircraft Type				
	(1) Air Carriers	(2) Air Taxis	(3) General Aviation	(4) Military	(5) Total
M1. Percent Diverted from Logan: (line 8 ÷ line 2) × 100	51.81	56.17	44.87	57.14	51.36
M2. Minutes Lost by Diverting Aircraft: line 8 × 30	20130	2730	2100	120	24960
M3. Total Delay of Delayed Landing and Diverted Aircraft: M2 + line 6	38354	4777	3776	209	46996
M4. Minutes Delay per Aircraft Scheduled for Logan: M3 ÷ line 2	29.62	29.49	24.20	29.86	29.01
M5. Minutes Spacing Delay per Aircraft: line 7 ÷ (line 8 + line 5)	5.97	4.73	0.11	0.22	5.30
M6. Average Landing Rate, Aircraft per Hour: line 9 ÷ 24	25.83	2.96	3.62	0.125	32.54
M7. Minutes Delay per Delayed Takeoff Aircraft: line 11 ÷ line 10	1.72	1.64	1.63	--	1.71
M8. Minutes Total Delay for Landing, Diverting, and Taking Off Aircraft: M3 + line 11	38942	4813	3838	--	47682
M9. Minutes Total Delay per Aircraft Scheduled for Logan: M8 ÷ line 2	30.07	29.71	24.60	--	29.43

Table 4-14. DELAY MATRIX - RUN 5

Run No. 5 Facility Status ASR, ARTS, ARSR, SECRA - Down All Day

WX: ☒ Random ☐ Controlled → Wind Direction ______ Ceiling ______
Wind Speed ______ Visibility ______

Delay Measure	Aircraft Type				
	Air Carrier	Air Taxi	General Aviation	Military	Totals
1. Number of Aircraft Created at Holding Fixes and Secondary Airports	1299	177	375	36	1887
2. Number of Aircraft Originally Scheduled to the Primary Airport Through the Holding Fixes	1295	162	156	7	1620
3. Number of Aircraft Diverted from Secondary Airport to Primary Airport	0	0	1	0	1
4. Time of Flight Accumulated by Secondary-Airport Aircraft Diverted to the Primary Airport	0	0	0	0	0
5. Number of Aircraft Landing at Primary Airport That Experienced Delay	190	26	37	2	255
6. Total Delay of Landing Aircraft	8778	1045	939	85	10847
7. Total Delay Accumulated, for Both Landing and Diverting Aircraft, Due to Separation Criteria	4615	536	30	26	5207
8. Number of Aircraft Not Able to Land at Primary Airport and Diverted	1080	136	113	5	1334
9. Number of Aircraft That Landed at Primary Airport	201	26	43	2	272
10. Number of Aircraft That Experienced Takeoff Delay at Primary Airport	197	25	42	2	266
11. Total Takeoff Delay Time	560	77	137	7	781
12. Total Takeoff Delay Time Experienced by Aircraft at Head of Takeoff Queue Waiting to Achieve Separation on Aircraft Taking Off Ahead	0	0	0	0	0
13. Number of Aircraft Entering the Takeoff Queue	NA	NA	NA	NA	NA

Table 4-15. MEASURES OF EFFECTIVENESS - RUN 5

Measure of Effectiveness	Aircraft Type				
	(1) Air Carriers	(2) Air Taxis	(3) General Aviation	(4) Military	(5) Total
M1. Percent Diverted from Logan: (line 8 ÷ line 2) × 100	83.40	83.95	72.43	71.43	82.34
M2. Minutes Lost by Diverting Aircraft: line 8 × 30	32400	4080	3390	150	40020
M3. Total Delay of Delayed Landing and Diverted Aircraft: M2 + line 6	41178	5125	4329	235	50867
M4. Minutes Delay per Aircraft Scheduled for Logan: M3 ÷ line 2	31.80	31.63	27.75	33.57	31.40
M5. Minutes Spacing Delay per Aircraft: line 7 ÷ (line 8 + line 5)	3.63	3.31	0.2	3.71	3.28
M6. Average Landing Rate, Aircraft per Hour: line 9 ÷ 24	8.375	1.08	1.79	0.08	11.33
M7. Minutes Delay per Delayed Takeoff Aircraft: line 11 ÷ line 10	2.84	3.08	3.26	3.5	2.94
M8. Minutes Total Delay for Landing, Diverting, and Taking Off Aircraft: M3 + line 11	41738	5202	4465	242	51648
M9. Minutes Total Delay per Aircraft Scheduled for Logan: M8 ÷ line 2	32.23	32.11	28.63	34.57	31.88

Table 4-16. DELAY MATRIX - RUN 6

Run No. 6 Facility Status All Up

WX: ☐ Random ☒ Controlled → Wind Direction N Ceiling 1000+
Wind Speed 10 Visibility 3+

Delay Measure	Aircraft Type				
	Air Carrier	Air Taxi	General Aviation	Military	Totals
1. Number of Aircraft Created at Holding Fixes and Secondary Airports	698	88	205	16	1007
2. Number of Aircraft Originally Scheduled to the Primary Airport Through the Holding Fixes	697	81	82	4	864
3. Number of Aircraft Diverted from Secondary Airport to Primary Airport	0	0	0	0	0
4. Time of Flight Accumulated by Secondary-Airport Aircraft Diverted to the Primary Airport	0	0	0	0	0
5. Number of Aircraft Landing at Primary Airport That Experienced Delay	465	45	47	2	559
6. Total Delay of Landing Aircraft	11288	1126	832	28	13274
7. Total Delay Accumulated, for Both Landing and Diverting Aircraft, Due to Separation Criteria	5088	585	11	2	5686
8. Number of Aircraft Not Able to Land at Primary Airport and Diverted	81	10	6	2	99
9. Number of Aircraft That Landed at Primary Airport	614	70	76	2	762
10. Number of Aircraft That Experienced Takeoff Delay at Primary Airport	321	29	30	0	380
11. Total Takeoff Delay Time	610	62	79	0	751
12. Total Takeoff Delay Time Experienced by Aircraft at Head of Takeoff Queue Waiting to Achieve Separation on Aircraft Taking Off Ahead	0	0	0	0	0
13. Number of Aircraft Entering the Takeoff Queue	614	62	76	2	754

Table 4-17. MEASURES OF EFFECTIVNESS - RUN 6

Measure of Effectiveness	Aircraft Type				
	(1) Air Carriers	(2) Air Taxis	(3) General Aviation	(4) Military	(5) Total
M1. Percent Diverted from Logan: (line 8 ÷ line 2) × 100	11.62	12.34	7.32	50.0	11.46
M2. Minutes Lost by Diverting Aircraft: line 8 × 30	2430	300	180	60	2970
M3. Total Delay of Delayed Landing and Diverted Aircraft: M2 + line 6	13718	1426	1012	88	16244
M4. Minutes Delay per Aircraft Scheduled for Logan: M3 ÷ line 2	19.68	17.60	12.34	22	18.80
M5. Minutes Spacing Delay per Aircraft: line 7 ÷ (line 8 + line 5)	9.32	10.64	0.21	0.5	8.64
M6. Average Landing Rate, Aircraft per Hour: line 9 ÷ 24	25.58	2.92	3.17	0.08	31.75
M7. Minutes Delay per Delayed Takeoff Aircraft: line 11 ÷ line 10	1.90	2.14	2.63	--	1.98
M8. Minutes Total Delay for Landing, Diverting, and Taking Off Aircraft: M3 + line 11	14328	1488	1091	--	16995
M9. Minutes Total Delay per Aircraft Scheduled for Logan: M8 ÷ line 2	20.05	18.37	13.30	--	19.67

4.3.7 Run 7 (Tables 4-18 and 4-19)

Run 7 is the "worst case" for the second set of runs, with all TRACON facilities down all day. Here the average landing rate per hour is 11.08, about the same as in run 5, indicating the nonradar approach environment. The number diverting is correspondingly high. Similarly M9, total delay per aircraft, is up to 33.77 minutes. This run, coupled with run 5, clearly shows the importance of TRACON radar facilities.

4.3.8 Run 8 (Tables 4-20 and 4-21)

Run 8 is identical to run 6 in all respects but one. Previously, the model had calculated the time of flight (TOF) from the holding fixes to Logan, using the aircraft's landing speed. In this run TOF is halved, equivalent to a transit speed twice the landing speed. This procedure, suggested by Boston TRACON personnel as being more representative of actual practice, has been retained in the model.

In order to examine the effects of this change, it will be necessary to establish a new measure of effectiveness, one not used before. Line 6 of the delay matrix is the total delay from all causes, i.e., time of landing, minus the time of flight, minus the time of aircraft generation. Line 7 is the delay due to spacing, i.e., placing the aircraft in the landing schedule. If line 7 is subtracted from line 6, the delay time due to factors other than spacing is obtained. If this time is divided by line 5, the number of delayed landing aircraft, an average delay per aircraft due to all factors other than placement on the landing schedule is obtained. For run 6 this measure, called M10, is 13.57 minutes, while for this run it is down to 10.05 minutes. The implication is that by moving the aircraft over the same distance from holding fix to airport at a higher speed, the controller frees himself more quickly to accept the next aircraft. However, M5, the minutes spacing delay, has increased from 8.64 minutes to 12.12 minutes per aircraft. This indicates that the delay burden has merely been shifted from the holding fixes to the landing schedule. This interpretation is given further support by noting that M4 and M9 (measures of total delay per aircraft) have both increased slightly. M1, the percentage of diversions, is down slightly. The results appear to be inconclusive; actually they are not. The results simply indicate that total delay is not materially changed merely by bringing aircraft in from the fixes faster, unless the runway acceptance rate is increased. This is a well known fact. That the model correctly conforms to reality in this case lends further credibility to the model's structure.

4.3.9 Run 9 (Tables 4-22 and 4-23)

This run is the same as run 8, except that the number scheduled to Logan was reduced to 568, about 24 per hour. The main purpose of this run was to further investigate model sensitivity to schedule intensity. The most apparent result is that no aircraft were diverted from Logan, and all delay measures were substantially reduced. The data also suggest

Table 4-18. DELAY MATRIX - RUN 7

Run No. 7 Facility Status ASR, ARTS 3, SECRA, ARSR - Down

WX: ☐ Random ☒ Controlled → Wind Direction N Ceiling 1000+

Wind Speed 10 Visibility 3+

Delay Measure	Aircraft Type				
	Air Carrier	Air Taxi	General Aviation	Military	Totals
1. Number of Aircraft Created at Holding Fixes and Secondary Airports	698	88	205	16	1007
2. Number of Aircraft Originally Scheduled to the Primary Airport Through the Holding Fixes	697	81	82	4	864
3. Number of Aircraft Diverted from Secondary Airport to Primary Airport	0	0	0	0	0
4. Time of Flight Accumulated by Secondary-Airport Aircraft Diverted to the Primary Airport	0	0	0	0	0
5. Number of Aircraft Landing at Primary Airport That Experienced Delay	184	33	29	2	248
6. Total Delay of Landing Aircraft	8390	1400	707	90	10587
7. Total Delay Accumulated, for Both Landing and Diverting Aircraft, Due to Separation Criteria	4192	656	26	30	4904
8. Number of Aircraft Not Able to Land at Primary Airport and Diverted	498	47	48	2	595
9. Number of Aircraft That Landed at Primary Airport	197	33	34	2	266
10. Number of Aircraft That Experienced Takeoff Delay at Primary Airport	197	29	34	2	262
11. Total Takeoff Delay Time	532	99	104	6	741
12. Total Takeoff Delay Time Experienced by Aircraft at Head of Takeoff Queue Waiting to Achieve Separation on Aircraft Taking Off Ahead	0	0	0	0	0
13. Number of Aircraft Entering the Takeoff Queue	197	29	34	2	262

Table 19. MEASURES OF EFFECTIVENESS - RUN 7

Measure of Effectiveness	Aircraft Type				
	(1) Air Carriers	(2) Air Taxis	(3) General Aviation	(4) Military	(5) Total
M1. Percent Diverted from Logan: (line 8 ÷ line 2) × 100	71.45	58.02	58.54	50.0	68.86
M2. Minutes Lost by Diverting Aircraft: line 8 × 30	14940	1410	1440	60	17850
M3. Total Delay of Delayed Landing and Diverted Aircraft: M2 + line 6	23330	2810	2147	150	28437
M4. Minutes Delay per Aircraft Scheduled for Logan: M3 ÷ line 2	33.47	34.69	26.18	37.5	32.91
M5. Minutes Spacing Delay per Aircraft: line 7 ÷ (line 8 + line 5)	6.15	8.2	0.34	7.5	5.82
M6. Average Landing Rate, Aircraft per Hour: line 9 ÷ 24	8.21	1.375	1.42	0.08	11.08
M7. Minutes Delay per Delayed Takeoff Aircraft: line 11 ÷ line 10	2.70	3.41	3.06	3.0	2.83
M8. Minutes Total Delay for Landing, Diverting, and Taking Off Aircraft: M3 + line 11	23862	2909	2251	156	29178
M9. Minutes Total Delay per Aircraft Scheduled for Logan: M8 ÷ line 2	34.24	35.91	27.45	39.0	33.77

Table 4-20. DELAY MATRIX - RUN 8

Run No. 8 Facility Status All Up

WX: ☐ Random ☒ Controlled → Wind Direction N Ceiling 1000+

Wind Speed 10 Visibility 3+

Delay Measure	Aircraft Type				
	Air Carrier	Air Taxi	General Aviation	Military	Totals
1. Number of Aircraft Created at Holding Fixes and Secondary Airports	698	88	205	16	1007
2. Number of Aircraft Originally Scheduled to the Primary Airport Through the Holding Fixes	697	81	82	4	864
3. Number of Aircraft Diverted from Secondary Airport to Primary Airport	0	0	0	0	0
4. Time of Flight Accumulated by Secondary-Airport Aircraft Diverted to the Primary Airport	0	0	0	0	0
5. Number of Aircraft Landing at Primary Airport That Experienced Delay	478	54	34	2	568
6. Total Delay of Landing Aircraft	11835	1306	539	68	13748
7. Total Delay Accumulated, for Both Landing and Diverting Aircraft, Due to Separation Criteria	7171	329	10	29	8039
8. Number of Aircraft Not Able to Land at Primary Airport and Diverted	78	7	9	1	95
9. Number of Aircraft That Landed at Primary Airport	619	73	73	3	768
10. Number of Aircraft That Experienced Takeoff Delay at Primary Airport	318	25	35	1	463
11. Total Takeoff Delay Time	628	64	80	1	773
12. Total Takeoff Delay Time Experienced by Aircraft at Head of Takeoff Queue Waiting to Achieve Separation on Aircraft Taking Off Ahead	0	0	0	0	0
13. Number of Aircraft Entering the Takeoff Queue	617	66	73	3	759

Table 4-21. MEASURES OF EFFECTIVENESS - RUN 8

Measure of Effectiveness	Aircraft Type				
	(1) Air Carriers	(2) Air Taxis	(3) General Aviation	(4) Military	(5) Total
M1. Percent Diverted from Logan: (line 8 ÷ line 2) × 100	11.19	8.64	10.97	25.0	10.99
M2. Minutes Lost by Diverting Aircraft: line 8 × 30	2340	210	270	30	2850
M3. Total Delay of Delayed Landing and Diverted Aircraft: M2 + line 6	14175	1516	809	98	16598
M4. Minutes Delay per Aircraft Scheduled for Logan: M3 ÷ line 2	20.34	18.72	9.86	24.5	19.21
M5. Minutes Spacing Delay per Aircraft: line 7 ÷ (line 8 + line 5)	12.90	13.59	0.23	9.67	12.12
M6. Average Landing Rate, Aircraft per Hour: line 9 ÷ 24	25.79	3.04	3.04	0.125	32.0
M7. Minutes Delay per Delayed Takeoff Aircraft: line 11 ÷ line 10	1.97	2.56	2.29	1.0	1.67
M8. Minutes Total Delay for Landing, Diverting, and Taking Off Aircraft: M3 + line 11	14803	1580	889	99	17371
M9. Minutes Total Delay per Aircraft Scheduled for Logan: M8 ÷ line 2	21.24	19.51	10.84	24.75	20.10

Table 4-22. DELAY MATRIX - RUN 9

Run No. 9 Facility Status All Up

WX: ☐ Random ☒ Controlled → Wind Direction N Ceiling 1000+
Wind Speed 10 Visibility 3+

Delay Measure	Aircraft Type Air Carrier	Air Taxi	General Aviation	Military	Totals
1. Number of Aircraft Created at Holding Fixes and Secondary Airports	460	38	134	10	642
2. Number of Aircraft Originally Scheduled to the Primary Airport Through the Holding Fixes	459	51	55	3	568
3. Number of Aircraft Diverted from Secondary Airport to Primary Airport	0	0	0	0	0
4. Time of Flight Accumulated by Secondary-Airport Aircraft Diverted to the Primary Airport	0	0	0	0	0
5. Number of Aircraft Landing at Primary Airport That Experienced Delay	218	26	7	0	251
6. Total Delay of Landing Aircraft	822	105	11	0	938
7. Total Delay Accumulated, for Both Landing and Diverting Aircraft, Due to Separation Criteria	822	105	11	0	938
8. Number of Aircraft Not Able to Land at Primary Airport and Diverted	0	0	0	0	0
9. Number of Aircraft That Landed at Primary Airport	458	51	55	3	567
10. Number of Aircraft That Experienced Takeoff Delay at Primary Airport	181	9	10	0	200
11. Total Takeoff Delay Time	257	15	12	0	284
12. Total Takeoff Delay Time Experienced by Aircraft at Head of Takeoff Queue Waiting to Achieve Separation on Aircraft Taking Off Ahead	0	0	0	0	0
13. Number of Aircraft Entering the Takeoff Queue	457	45	55	1	558

Table 4-23. MEASURES OF EFFECTIVENESS - RUN 9

Measure of Effectiveness	Aircraft Type (1) Air Carriers	(2) Air Taxis	(3) General Aviation	(4) Military	(5) Total
M1. Percent Diverted from Logan: (line 8 ÷ line 2) × 100	0	0	0	0	0
M2. Minutes Lost by Diverting Aircraft: line 8 × 30	0	0	0	0	0
M3. Total Delay of Delayed Landing and Diverted Aircraft: M2 + line 6	822	105	11	0	938
M4. Minutes Delay per Aircraft Scheduled for Logan: M3 ÷ line 2	1.79	2.06	0.2	0	1.65
M5. Minutes Spacing Delay per Aircraft: line 7 ÷ (line 8 + line 5)	3.77	4.03	1.57	--	3.73
M6. Average *Landing Rate*, Aircraft per Hour: line 9 ÷ 24	19.08	2.125	2.29	--	23.62
M7. Minutes Delay per Delayed Takeoff Aircraft: line 11 ÷ line 10	1.42	1.67	1.2	--	1.42
M8. Minutes Total Delay for Landing, Diverting, and Taking Off Aircraft: M3 + line 11	1079	120	23	--	1222
M9. Minutes Total Delay per Aircraft Scheduled for Logan: *M8 ÷ line 2*	2.35	2.35	0.42	--	2.15

an interaction between schedule and time of flight. Since in this run the arrival rate is below the runway acceptance rate, estimated at about 32 aircraft per hour for runs 1 and 6, total delay per aircraft should be reduced by bringing the aircraft in faster from the holding fixes. One way of verifying this hypothesis would be to make another run with this low arrival rate and with the transit speed reduced to the landing speed, as in run 6.

4.3.10 Run 10 (Tables 4-24 and 4-25)

Run 10 was designed to test the runway selection module, as explained in Section 4.1. The delay measures for this run are all compatible with the higher aircraft arrival rate, as compared with run 9. It should be noted that the ASR being down had no effect on model operation except for forcing landings on runway 4 instead of 33.

One notable exception displayed by this run is in M7, the minutes of delay per delayed-takeoff aircraft. The figure of 3.43 minutes is the highest of all the runs. The reason for this is that when the wind exceeds 15 knots, 18 knots in this case, and the weather is IFR, all landings and takeoffs take place on the same runway; thus aircraft taking off are more likely to be delayed.

A final item of interest in this run is the diversion to Logan of aircraft scheduled to secondary airports because of the low ceiling and visibility, assumed to prevail throughout the TCA. This happened only once in the first five runs, and not at all in runs 6 through 9. The interpretation of this result is that the weather module was in place during the first five runs and set in the random mode. For some brief period during the 24-hour simulated day, it must have been below minima for one of the secondary airports. During runs 6 through 9 the weather was forced to VFR, and under this condition the model lands all aircraft scheduled for secondary airports. If runs 9 and 10 were to be conducted with identical aircraft generation rates and wind conditions, the crowding effect of aircraft diverted from secondary airports on Logan traffic could be ascertained.

4.4 ANALYSIS OF DEMONSTRATION RUNS

The principal findings contained in the data presented are displayed graphically in Figures 4-1 through 4-5, and discussed in Section 4.4.1 through 4.4.5.

4.4.1 M-1, Percentage of Aircraft Diverted from Logan

Figure 4-1 shows clearly the combined effects of schedule intensity and TRACON facility outage. Runs 1 through 4 are strongly affected by the high arrival rate, while run 5 has this effect compounded by TRACON facilities outage. Run 7, also with TRACON facilities out, shows the same pronounced effect -- uncoupled as it is from the schedule effect.

Table 4-24. DELAY MATRIX - RUN 10

Run No. 10 Facility Status ASR - Down

Wx: ☐ Random ☒ Controlled → Wind Direction N Ceiling 600
Wind Speed 18 Visibility 1.5

Delay Measure	Aircraft Type				
	Air Carrier	Air Taxi	General Aviation	Military	Totals
1. Number of Aircraft Created at Holding Fixes and Secondary Airports	515	64	160	12	751
2. Number of Aircraft Originally Scheduled to the Primary Airport Through the Holding Fixes	514	50	87	8	659
3. Number of Aircraft Diverted from Secondary Airport to Primary Airport	0	0	21	4	25
4. Time of Flight Accumulated by Secondary-Airport Aircraft Diverted to the Primary Airport	0	0	462	83	545
5. Number of Aircraft Landing at Primary Airport That Experienced Delay	356	33	60	4	453
6. Total Delay of Landing Aircraft	7419	801	1418	91	9729
7. Total Delay Accumulated, for Both Landing and Diverting Aircraft, Due to Separation Criteria	4694	629	968	49	6340
8. Number of Aircraft Not Able to Land at Primary Airport and Diverted	51	9	6	2	68
9. Number of Aircraft That Landed at Primary Airport	462	47	81	6	596
10. Number of Aircraft That Experienced Takeoff Delay at Primary Airport	346	29	56	2	433
11. Total Takeoff Delay Time	1252	80	153	2	1487
12. Total Takeoff Delay Time Experienced by Aircraft at Head of Takeoff Queue Waiting to Achieve Separation on Aircraft Taking Off Ahead	39	2	4	0	45
13. Number of Aircraft Entering the Takeoff Queue	461	44	81	2	588

Table 4-25. MEASURES OF EFFECTIVENESS - RUN 10

Measure of Effectiveness	Aircraft Type				
	(1) Air Carriers	(2) Air Taxis	(3) General Aviation	(4) Military	(5) Total
M1. Percent Diverted from Logan: (line 8 ÷ line 2) × 100	9.99	18.0	6.9	25.0	10.32
M2. Minutes Lost by Diverting Aircraft: line 8 × 30	1530	270	180	60	2040
M3. Total Delay of Delayed Landing and Diverted Aircraft: M2 + line 6	8949	1071	1598	151	11769
M4. Minutes Delay per Aircraft Scheduled for Logan: M3 ÷ line 2	17.41	21.42	18.37	18.87	17.86
M5. Minutes Spacing Delay per Aircraft: line 7 ÷ (line 8 + line 5)	11.53	14.98	14.67	8.16	12.17
M6. Average Landing Rate, Aircraft per Hour: line 9 ÷ 24	19.25	1.96	3.37	0.25	24.83
M7. Minutes Delay per Delayed Takeoff Aircraft: line 11 ÷ line 10	3.62	2.76	2.73	1.0	3.43
M8. Minutes Total Delay for Landing, Diverting, and Taking Off Aircraft: M3 + line 11	10201	1151	1751	153	13256
M9. Minutes Total Delay per Aircraft Scheduled for Logan: M8 ÷ line 2	19.85	23.02	20.13	19.125	20.11

Run Number	Facility Status	Weather	Number of Aircraft Generated
1	ASR, ARTS, ARSR, SECRA up - rest random	Random, VFR probably	1887
2	ARTS and SECRA down all day	Same	1887
3	ASR, ARTS, ARSR, SECRA down from 5-7 p.m.	Same	1887
4	ARTS, SECRA down from 5-7 p.m.	Same	1887
5	ASR, ARTS, ARSR, SECRA down all day	Same	1887

Run Number	Facility Status	Wind D/V	Ceiling (Feet)	Visibility (Miles)	Number of Aircraft Generated	Aircraft Speed from Holding Fix to Logan
6	All up	N/10	1000+	3+	1007	Landing Speed
7	ASR, ARTS, SECRA, ARSR down	N/10	1000+	3+	1007	Landing Speed
8	All up	N/10	1000+	3+	1007	2 × Landing Speed
9	All up	N/10	1000+	3+	662	2 × Landing Speed
10	ASR down	N/18	600	1.5	751	2 × Landing Speed

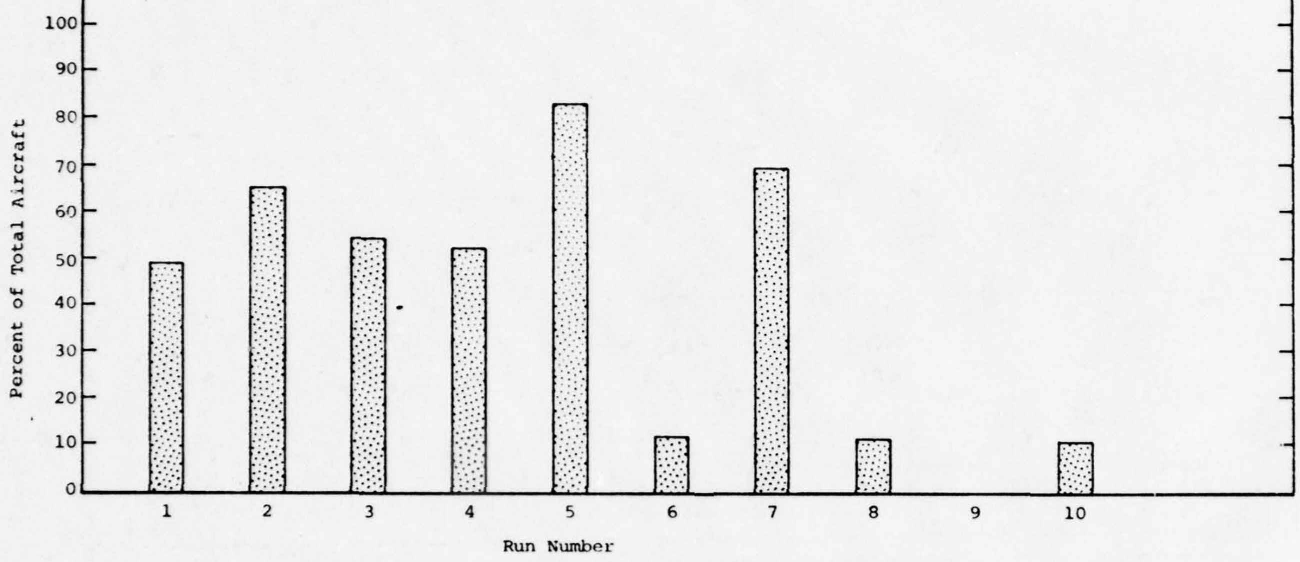
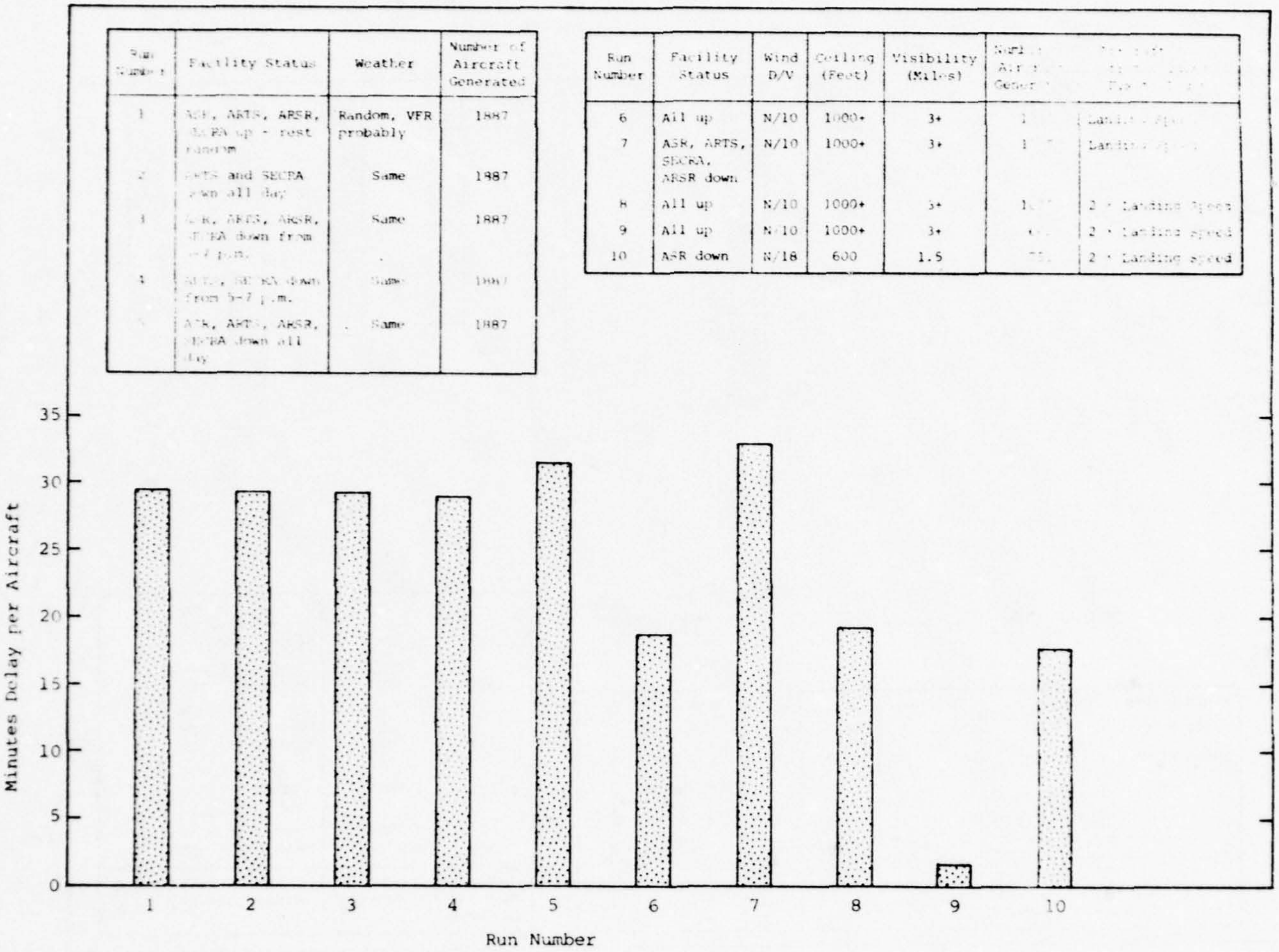


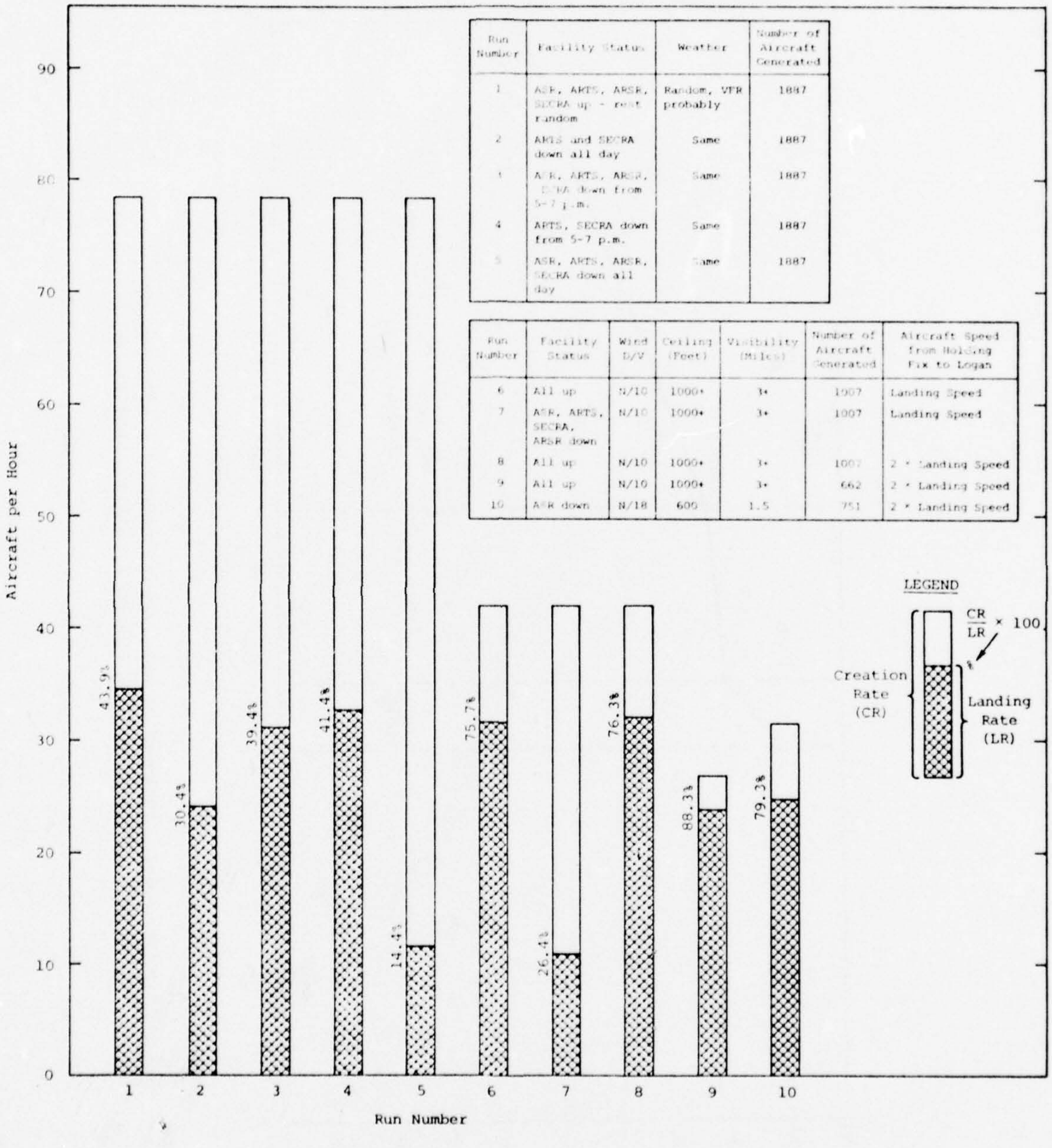
Figure 4-1. M-1 PERCENTAGE OF TOTAL AIRCRAFT DIVERTED FROM LOGAN



Run Number	Facility Status	Weather	Number of Aircraft Generated
1	ASR, ARTS, ARSR, SECRA up - rest random	Random, VFR probably	1887
2	ARTS and SECRA down all day	Same	1887
3	ASR, ARTS, ARSR, SECRA down from 5-7 p.m.	Same	1887
4	ARTS, SECRA down from 5-7 p.m.	Same	1887
5	ASR, ARTS, ARSR, SECRA down all day	Same	1887

Run Number	Facility Status	Wind D/V	Ceiling (Feet)	Visibility (Miles)	Number of Aircraft Generated	[illegible]
6	All up	N/10	1000+	3+	[illegible]	Landing Speed
7	ASR, ARTS, SECRA, ARSR down	N/10	1000+	3+	[illegible]	Landing Speed
8	All up	N/10	1000+	3+	[illegible]	2 × Landing Speed
9	All up	N/10	1000+	3+	[illegible]	2 × Landing speed
10	ASR down	N/18	600	1.5	[illegible]	2 × Landing speed

Figure 4-2. M-4 MINUTES DELAY PER AIRCRAFT SCHEDULED FOR LOGAN



Run Number	Facility Status	Weather	Number of Aircraft Generated
1	ASR, ARTS, ARSR, SECRA up - rest random	Random, VFR probably	1887
2	ARTS and SECRA down all day	Same	1887
3	ASR, ARTS, ARSR, SECRA down from 5-7 p.m.	Same	1887
4	ARTS, SECRA down from 5-7 p.m.	Same	1887
5	ASR, ARTS, ARSR, SECRA down all day	Same	1887

Run Number	Facility Status	Wind D/V	Ceiling (Feet)	Visibility (Miles)	Number of Aircraft Generated	Aircraft Speed from Holding Fix to Logan
6	All up	N/10	1000+	3+	1007	Landing Speed
7	ASR, ARTS, SECRA, ARSR down	N/10	1000+	3+	1007	Landing Speed
8	All up	N/10	1000+	3+	1007	2 × Landing Speed
9	All up	N/10	1000+	3+	662	2 × Landing Speed
10	ASR down	N/18	600	1.5	751	2 × Landing Speed

Figure 4-3. M-6 AVERAGE LANDING RATE, AIRCRAFT PER HOUR AND CREATION RATE IN AIRCRAFT PER HOUR

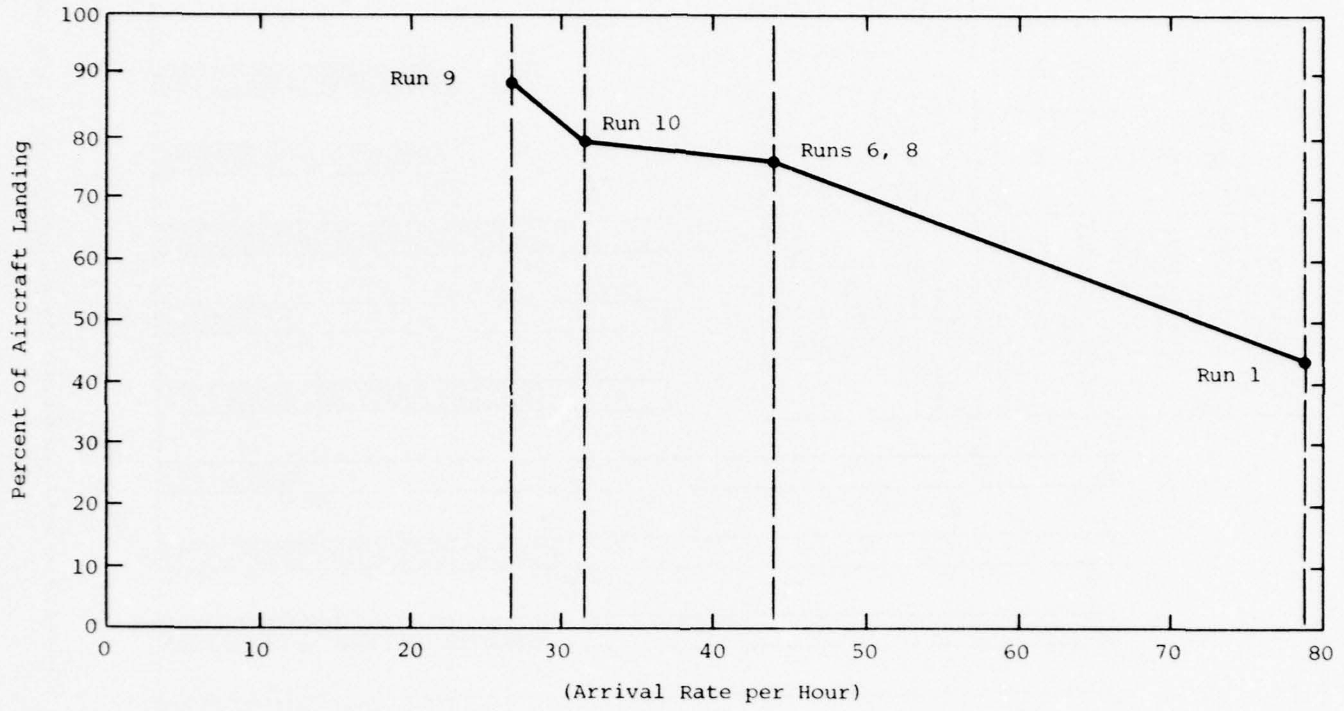
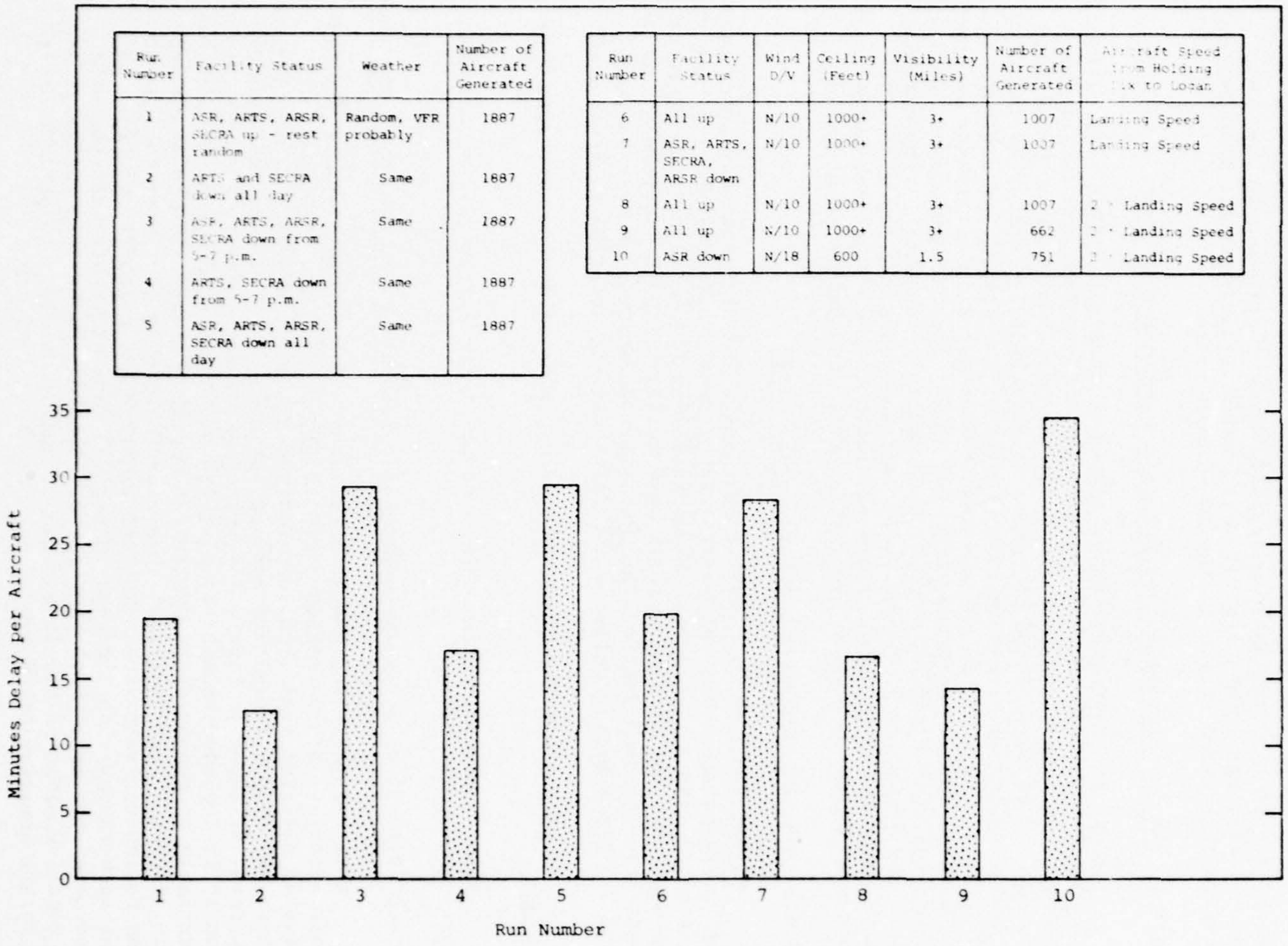


Figure 4-4. PERCENT OF AIRCRAFT LANDING AS A FUNCTION OF ARRIVAL RATE PER HOUR, ALL FACILITIES UP



Run Number	Facility Status	Weather	Number of Aircraft Generated
1	ASR, ARTS, ARSR, SECRA up - rest random	Random, VFR probably	1887
2	ARTS and SECRA down all day	Same	1887
3	ASR, ARTS, ARSR, SECRA down from 5-7 p.m.	Same	1887
4	ARTS, SECRA down from 5-7 p.m.	Same	1887
5	ASR, ARTS, ARSR, SECRA down all day	Same	1887

Run Number	Facility Status	Wind D/V	Ceiling (Feet)	Visibility (Miles)	Number of Aircraft Generated	Aircraft Speed from Holding Fix to Logan
6	All up	N/10	1000+	3+	1007	Landing Speed
7	ASR, ARTS, SECRA, ARSR down	N/10	1000+	3+	1007	Landing Speed
8	All up	N/10	1000+	3+	1007	2 × Landing Speed
9	All up	N/10	1000+	3+	662	2 × Landing Speed
10	ASR down	N/18	600	1.5	751	2 × Landing Speed

Figure 4-5. M-7 MINUTES DELAY PER DELAYED TAKEOFF AIRCRAFT

Runs 6, 8, 9 and 10 show, primarily, the decreased number of diversions due to the less intense arrival rate. As previously discussed, run 9, with the lowest arrival rate, shows no diversions. This result can be attributed solely to the low arrival rate.

4.4.2 M-4, Minutes Delay per Aircraft Scheduled for Logan

Figure 4-2 displays several points of interest. First, for runs 1 through 5 this measure totally confounds the schedule and facilities outage effect, with no appreciable difference attributable to facility outage. Runs 6, 7, 8 and 10 appear to be responsive mostly to facility outage, while run 9 is totally dominated by the much lower arrival rate. Comparing runs 9 and 10 reveals that this measure is critically dependent on arrival rate in the range from 662 to 751 aircraft per day. Similarly, comparing runs 8 and 10, for which the arrival rates are, respectively, 1007 and 751 per day, shows little variation in delay per aircraft. Whether or not these numbers are accurate, they do show that there is a point at which the system becomes saturated and delays mount rapidly.

4.4.3 M-6, Average Handling Rate per Aircraft

Figure 4-3 combines several features. The cross-hatched lower portions of the bar graphs show the landing rate, in aircraft per hour, by run number. The total length of the bars shows the aircraft creation rate. Here it can be seen that the landing rate is essentially schedule-independent and is most strongly dependent on TRACON facilities status, as seen in runs 2, 5, and 7. Run 9 merely reflects the fact that the creation rate was low.

The percentage figures are the proportion of created aircraft that are landed.

This figure strengthens the concept of the system filling and then turning away the excess.

4.4.4 Percent of Aircraft Landing as a Function of Arrival Rate per Hour

This paragraph represents an alternative interpretation of arrival-rate effects. If the ratios shown in Figure 4-3, the percentage of created aircraft that land, are plotted against the arrival rates for runs where all TRACON facilities were up, then an almost linear relationship appears, as shown in Figure 4-4. The runs chosen were 1, 6, 8, 9, and 10. Run 10 is included because even though the ASR was down, an approach was available on runway 4 and controller capacity and trail separation were not affected. The fact that this measure is slightly lower for run 10 can be indicative of the effect of landings and takeoffs occurring on the same runway. An increase in arrival rate of 52 aircraft per hour decreases the percentage that actually land by about 45 percent, giving a negative slope in the data range of approximately 1.15 percent per aircraft arriving per hour.

4.4.5 M-7, Minutes Delay per Delayed-Takeoff Aircraft

Figure 4-5 shows that takeoff delays too are responsive to several factors. The first and most obvious is wind speed, seen in run 10.

Runs 3, 5, and 7 show the effect of three-minute separation between aircraft taking off when the TRACON facilities are down. It would seem, at first, that the results of runs 1, 2, and 4 are contradictory, since runs 2 and 4 have the ARTS and SECRA down all day and from 5 to 7 P.M., respectively. The effect here, however, is not that takeoff separation is increased, because with the ASR up, it is not. The dominant cause is seen in Figure 4-3, which shows that fewer aircraft are landing. Because of the turnaround feature in the model, the fewer aircraft arriving, the fewer appear at the takeoff queue, and the less they are affected by separation on landing aircraft.

4.5 SUMMARY

While other delay measures are possible, those chosen were thought to be useful and adequate and have in fact been shown to be highly descriptive of delay behavior and strongly sensitive to the three delay-inducing factors: facility outage, schedule intensity, and weather.

It is not possible without verifying the model against actual system performance to know if the absolute values are correct, or whether their degree of response to factor change is accurate. Even so, the model is responsive in the right sense; i.e., the measure responses increase and decrease in the expected directions.

CHAPTER FIVE

FACILITY MAINTENANCE COST MODEL

5.1 DESCRIPTION OF THE COST DETERMINATION PROCESS

The Facility Maintenance Cost Model was formulated to evaluate labor costs associated with maintaining FAA facilities within a maintenance sector. The model determines these costs by computing the number of maintenance and supervisory personnel required to perform all corrective maintenance (CM) and preventive maintenance (PM), with proper allowance for personnel productivity. The basic cost-determination process that is modeled is depicted in Figure 5-1. For corrective maintenance, mean time between corrective maintenance actions (MTBCMA) and mean time to restore (MTTR) are used to determine the expected number of corrective maintenance actions and expected repair times per action. For each action, man-hour demands, by skill level, are incurred for direct maintenance action, as well as travel time on level C facilities.* Man-hour demands are similarly determined for preventive maintenance. Total man-hour requirements are summed over all facility types for the sector. These are then converted to numbers of personnel required for each skill level, and the numbers are then used to determine support personnel. These total manpower requirements are then combined with wage rates and salaries to determine the annual sector labor costs.

5.2 OVERVIEW OF THE MODEL AND ITS CAPABILITIES

It is recognized that personnel costs represent 80 percent of the FAA maintenance costs. Consequently, TSC encouraged the development of a model that would focus on this single key maintenance-cost factor. Therefore, the FMCM has been designed to predict required maintenance staff levels and associated costs on the basis of the expected annual requirements for corrective and preventive maintenance, the desired facility-restoration levels, and personnel productivity factors. The FMCM evaluates the expected direct labor and salary costs for a one-year interval. The model has been formulated to evaluate both the preventive maintenance and corrective maintenance

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*There are three facility-restoration levels. Level A facilities are not repaired outside normal working hours. Level B facilities that fail outside normal working hours are repaired, if possible, by calling maintenance personnel back. Facilities subject to level C restoration are attended by three shifts of maintenance personnel on a 24-hour basis.

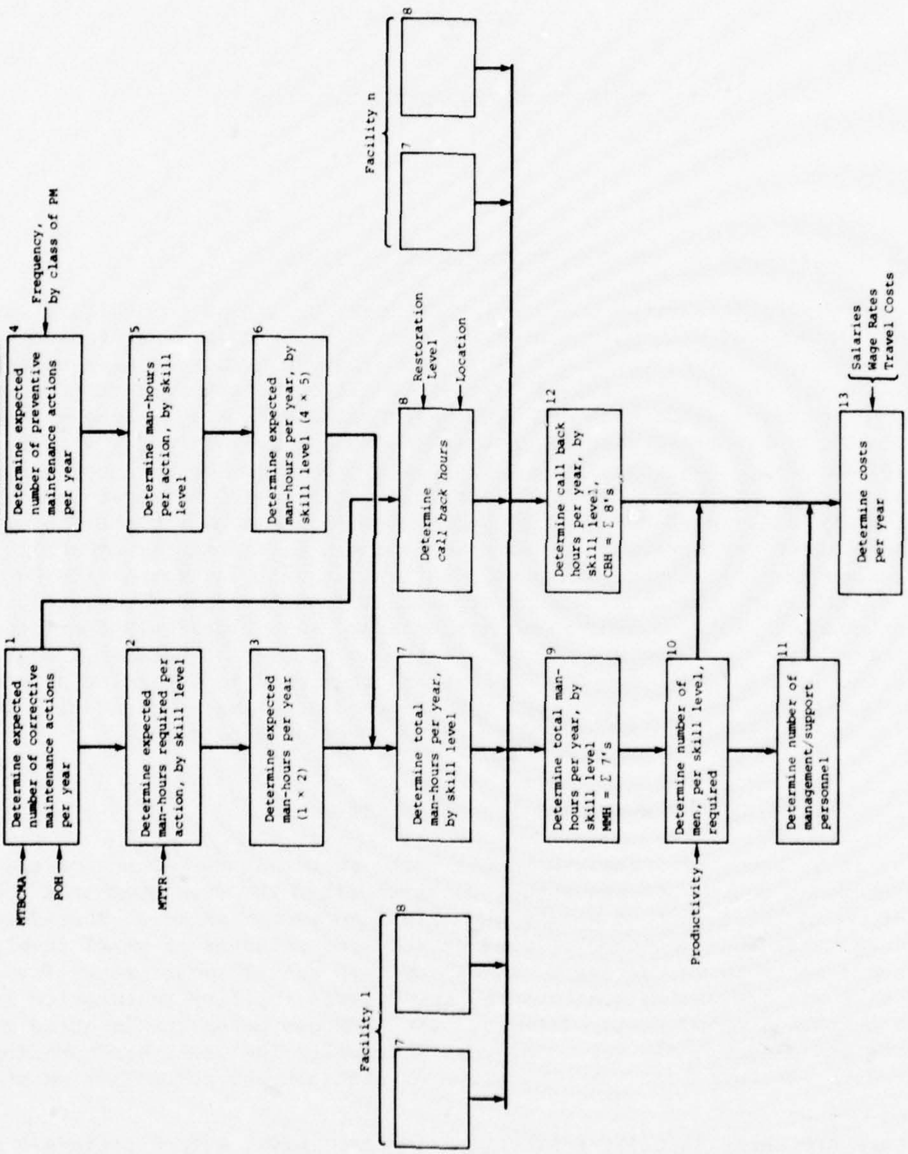


Figure 5-1. COSTS OF MAINTENANCE LABOR ANALYSIS

required by any single facility type, accumulate staffing and cost data for the facility type within the specified maintenance sector, evaluate all other designated types of facilities within the sector, and accumulate total sector maintenance costs.

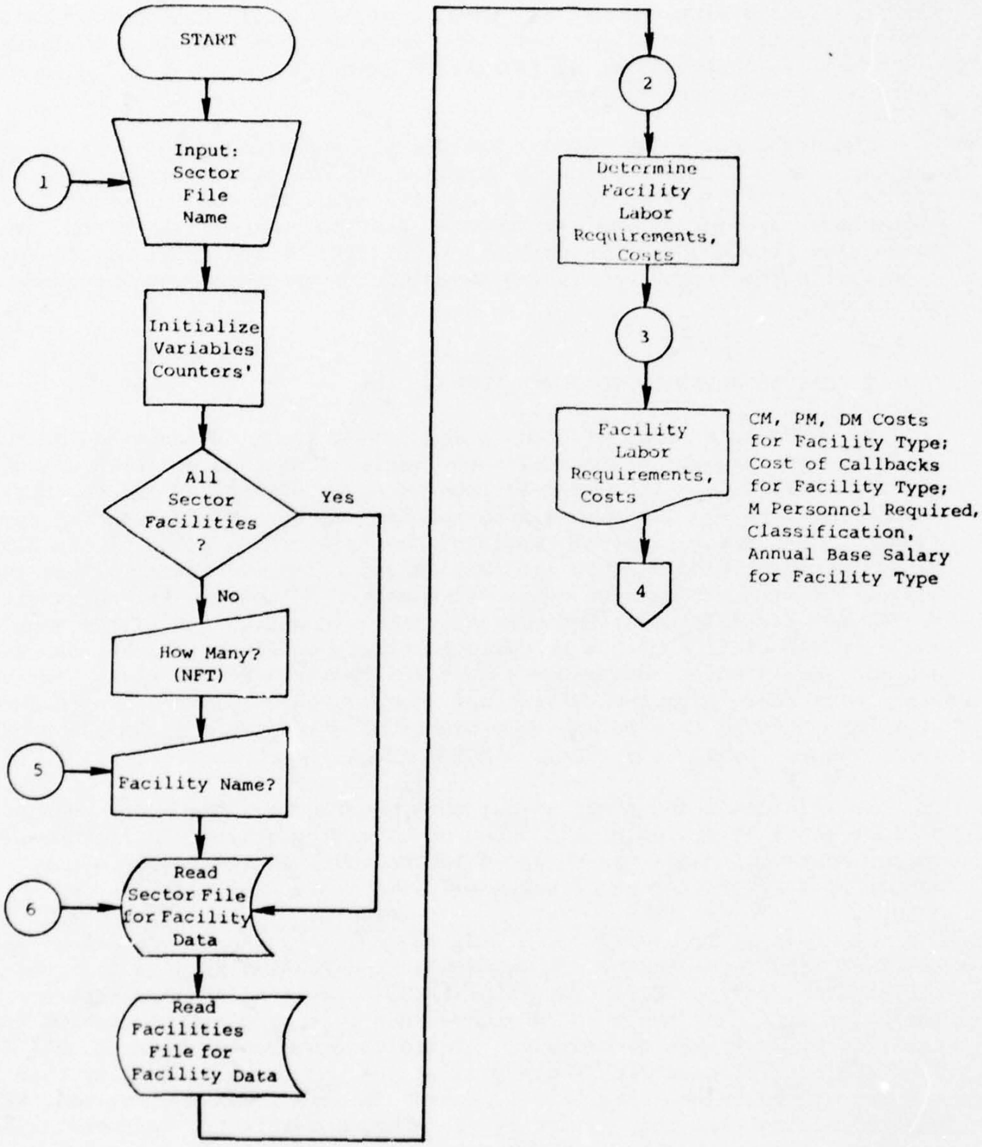
The principal model outputs include the expected annual cost of maintaining a specific facility type within a sector, the required number of personnel by skill level for that facility type, the cost of preventive maintenance and corrective maintenance, and the cost of call-backs. The model also provides similar cost and labor data on the total of all facilities within the sector, including management/support personnel requirements and costs.

5.3 TECHNICAL APPROACH TO MODEL FORMULATION

The FMCM is an analytic model, comprising a set of equations designed to calculate the expected annual labor costs of maintenance within a given maintenance sector. The model is programmed in FORTRAN IV and has been demonstrated on the CDC Kronos time-sharing system. By running the model from a time-sharing terminal, maximum advantage can be taken of its ability to evaluate selected sectors and facilities, print the results, then run again, all in a man-machine interactive mode. A program listing is provided in separately published documentation. Construction of the model required recognition of the predominant effect of labor on maintenance costs and the way in which this labor effect manifests itself on cost. Interviews with maintenance personnel of the New England Region and the Boston Sector were conducted so that maintenance practices common to the FAA and peculiar to the Region could be reflected in the model.

It is significant that, as currently configured, the model does not include costs of spares provisioning or other logistics support costs. These additional costs can be added to the model incrementally without requiring a restructuring of the model as it currently exists.

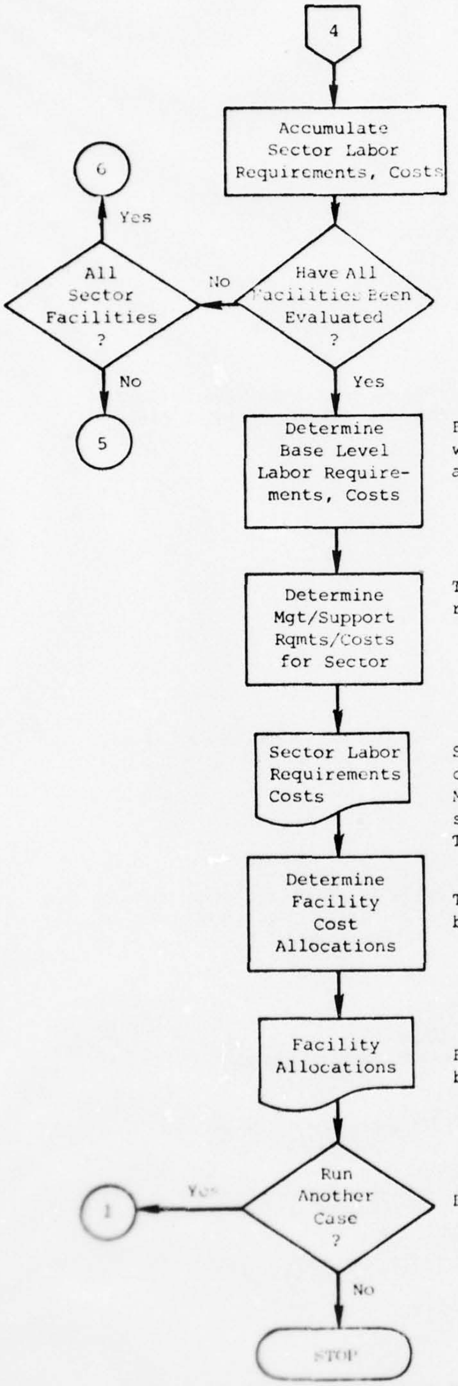
As shown in Figures 5-2 and 5-3, the model begins by accepting, as a terminal input, the sector file name and then reading in data from the sector file (called SECFIL) describing the overall maintenance characteristics of the sector to be evaluated and data peculiar to each of the facility types within the sector. (These data are shown in Section 5.4.) Then the analyst specifies whether or not he wants every facility type in the sector evaluated. If only selected facility types are desired, he must then input how many of the facility types within the sector will be considered in the analysis, together with their identifiers. The analysis begins by considering each facility type separately. To evaluate each facility type, an additional file (called FACFIL) containing facility data common to all facilities of that type throughout the FAA system is required. On the basis of the sector and facility file data, the corrective maintenance (CM), preventive maintenance (PM), and their sum, direct maintenance (DM), are computed and presented as intermediate output data. After these manpower requirements have been computed separately for each facility type, they are combined to determine the total personnel requirements for the maintenance sector.



CM, PM, DM Costs for Facility Type; Cost of Callbacks for Facility Type; M Personnel Required, Classification, Annual Base Salary for Facility Type

(continued)

Figure 5-2. FMCM LOGIC



I = NFT?

For cases where facility site CM action was remove & replace, with repair occurring at centralized "base" activity

Table lookup for management/support personnel required to support site and base M personnel

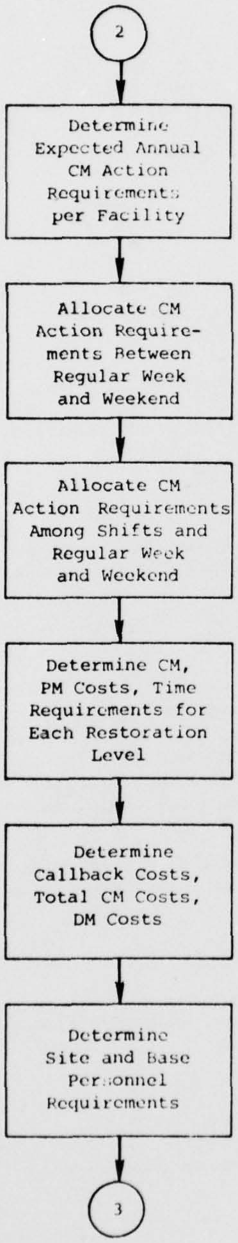
Sector CM, PM, DM costs; M personnel by classification, with annual base salaries; Management personnel, with annual base salaries; Total sector callback costs; Total sector labor costs; Base salaries

Total sector costs/salaries allocated back by percent of sector population

Facility name, quantity, allocated costs, and base salaries

Evaluate another sector, other facility types

Figure 5-2. (continued)



XNOF = AOH/MTBCMA

These allocations reflect when failure occurs, not when CM action takes place

CM costs, demands are determined for all but callback (B) actions

For all facilities of type, accumulate 3 restoration levels. Total CM costs = CM costs + callback costs

$DM = CM_{(total)} + PM$

Annual Demand (PM + CM)/2080-Productivity = NPERS

DM demand includes safety factor to ensure availability of personnel; based on Poisson distribution

Figure 5-3. FMCM LOGIC (EXPANSION BETWEEN PARTS 2 AND 3)

The combined man-hour requirements are translated into specific staffing levels for each of the maintenance skill levels defined in the input data. Through this procedure realistic staffing levels are developed wherein personnel of the same skill category may work on several facility types. Having determined the number of maintenance personnel, the model uses a table lookup (see Table 5-1) to determine the number of management/support personnel. Total personnel costs are calculated in the model by summing the product of personnel requirements, in man-hours, and the wage rate over the labor classes required.

Table 5-1. RELATIONSHIP BETWEEN MAINTENANCE PERSONNEL AND MANAGEMENT/SUPPORT PERSONNEL

Number of Maintenance Personnel	Number of Management/Support Personnel
0 - 4	0
5	3
6	4
7	5
8	8
9	9
10	10
11	11
12	12
13	13
14 - 23	15
24 - 33	17
34 - 43	19
44 - 53	21
54 - 63	23
64 - 73	25
74 - 83	27
84 - 93	29
94 - 103	31

At the end of the analysis, total sector maintenance requirements and costs and facility cost allocations are printed. At the option of the analyst, the program can then either terminate or return to the beginning for another program execution. The key cost categories that the model considers are defined in the following subsections.

5.3.1 Preventive Maintenance

Preventive maintenance (PM) cost is determined by the maintenance man-hour expenditures required in accordance with preventive maintenance schedules published in DOT orders applicable to the facilities under evaluation and travel time. Daily preventive maintenance actions are assumed to require travel times different from those for the longer PM actions, which are all assumed to be the same as for a CM action. This is done to reflect facility-to-facility travel for daily PM rather than travel from the central maintenance location to the facility assumed for the other actions.

Preventive maintenance is assumed to be performed during normal work hours only. It does, however, affect the overall staffing requirements for the facility type and maintenance sector.

5.3.2 Corrective Maintenance

Corrective maintenance (CM) actions are those initiated by failure within a facility. The failure may be catastrophic, caused by a component failure; or it may be one caused by performance degradation below the tolerances specified in DOT orders for facility operations. Either type of failure will normally require replacement of components, modules, or entire systems, depending on the severity of the failure.

The model assumes that all failures are scheduled for immediate repair during normal duty hours and that they preempt preventive maintenance requirements. Corrective action considers the manpower required to restore a facility and includes the transportation time from normal duty station to the failed facility, test and diagnostic setup time, fault-isolation time, time to repair, operational test time, and transportation time to return to normal duty station.

Failures occurring during off-duty hours are scheduled for repair during normal duty hours if the failed system has a restoration level A, or scheduled for repair by call-back personnel if the system has a restoration level B. Call-back repairs are subject to premium overtime rates for labor and include the additional time authorized for transportation between the technician's home and his normal duty station. Level B system failures are repaired the next normal working day if contact with call-back personnel is not established.

Facilities categorized as restoration level C are normally manned 24 hours per day. Therefore, failures of systems in these facilities are treated the same as normal duty system failures except that the labor rates are increased to reflect a shift differential.

5.3.3 Direct Maintenance

The direct maintenance (DM) is the sum of the preventive maintenance and the corrective maintenance. This quantity represents the total maintenance labor demand for the facility and/or maintenance sector.

5.3.4 Personnel Requirements

The model computes the minimum number of personnel of a given skill category required to perform all expected preventive and corrective maintenance for each facility type. Personnel requirements are determined through the application of productivity factors, which include corrective maintenance and preventive maintenance times (both of which include transportation time) as the baseline (direct labor) and all other labor categories such as training, watch-standing, leave, vacation, etc., as nonproductive activities. The model includes as an output the actual productivity of each labor class, which takes into account the foregoing factors plus any minimum manning constraints (e.g., level C manning requires at least 3 maintenance personnel per day).

The model will permit consideration of an alternative scenario in which some failed items are repaired at an intermediate repair facility, with the site repair activity then becoming simply a remove and replace action. The extent of this option is established within the sector file by the variable RTS (fraction of failures repaired directly at the site). The model automatically determines the number of required intermediate-level personnel and their associated costs based on the input values of RTS for each facility type ($0 \leqslant RTS \leqslant 1$). The model also determines the number of management/support personnel required for the established maintenance personnel based on FAA standards; it determines their costs and includes these costs in the total costs (direct labor and salary) for the sector.

5.4 DATA REQUIRED TO EXERCISE THE MODEL

The descriptions of the contents of the sector data file and the facilities data file are shown in Tables 5-2 and 5-3, respectively. The numerical data used in the model demonstration are given in Chapter Six.

5.5 DESCRIPTION OF MODEL OUTPUTS

Figures 5-4 through 5-6 are reproductions of outputs of model runs performed during the demonstration of the model (discussed in Chapter Six). Figure 5-4 shows a run in which all facility types in the Logan Sector are evaluated. The figure is truncated to show only the outputs associated with the first five facility types, out of a total of fourteen.

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Table 5-2. SECTOR DATA FILE (SECFIL)

Mnemonic	Description
NFT	Number of facilities in the sector data file
NSL	Number of skill levels available within the sector
MLR	Average management support labor rate (dollars per hour)
BLR	Intermediate maintenance shop labor rate (dollars per hour)
PRODB	Intermediate maintenance shop labor productivity ratio
XXX	Mnemonic for maintenance skill level
SLR	Labor rate (dollars per hour, defined for each skill level)
① PSLR	Overtime labor rate (dollars per hour, defined for each skill level)
SDIF	Shift differential (a factor defined for each skill level)
MPER	Management support requirements as a function of maintenance staff size
XXX	Mnemonic for a facility type within the sector
AOH	Average annual facility operating hours (hours per year)
DOH	Average daily facility operating hours (hours per day)
PCONB	Probability of contacting a maintenance man for a restoration level B facility
RTS	Fraction of failures repaired directly at the site
PROD	Average maintenance man productivity
② NSCAT	Maintenance skill level identifier (see Note 1)
NRLA/NRLB/NRLC	Number of facilities having restoration levels A, B, or C
NDSA/NDSB/NDSC	Number of daily shifts for facilities having restoration levels A, B, or C
NWSA/NWSB/NWSC	Number of weekend shifts for facilities having restoration levels A, B, or C
TRTP	Average authorized travel time to one of these facilities for a call-back (hours)
TRT	Average travel time to one of these facilities from the central location (hours)
TRTD	Average travel time to one of these facilities for daily PM (hours)

Notes: 1. These parameters are repeated for each skill level available within the sector.
2. These parameters are repeated for each facility type within the sector.

Table 5-3. FMCM FACILITIES DATA FILE FOR EACH FACILITY TYPE (FACFIL)

Mnemonic Code*	Description
Alphanumeric	Alphanumeric identifier for facility type (e.g., GS, ASR, LOM)
MTBCMA	Mean time between corrective maintenance actions (operating hours per failure)
SUF	Personnel sufficiency factor (nondimensional factor to provide safety margin in determining personnel requirements)
FITT	Average fault-isolation and test time (maintenance man-hours per action)
MTTR	Mean time to repair (maintenance man-hours per action)
MTRR	Mean time to remove and replace (maintenance man-hours per action)
BMMH	Average intermediate-level repair time (maintenance man-hours per action)
PMMH	Preventive maintenance time (maintenance man-hours per action)**

*These parameters are repeated for each facility type within the sector.

**This parameter is an array of preventive maintenance times, by facility type, for each of the following scheduled PM frequencies: daily, weekly, monthly, quarterly, semi-annually, annually, three times daily, every other day, twice a week, every other week.

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```
              AIRWAYS - FACILITIES MAINTENANCE SECTOR COSTS


INPUT SECTOR FILE NAME ? LOGAN
DO YOU WANT TO CONSIDER ALL FACILITY TYPES ? YES


FACILITY = ASR
CM COST =     501.21  PM COST =  23535.00  DM COST =  24036.21
COST OF CALLBACKS =        0.
   2 OF SITE LABOR CLASS  RAD          AT ANNUAL BASE COST =  49920.00
   0 OF BASE LABOR CLASS AT ANNUAL COST =        0.


FACILITY = ARSR
CM COST =     359.64  PM COST =  20970.00  DM COST =  21329.64
COST OF CALLBACKS =        0.
   2 OF SITE LABOR CLASS  RAD          AT ANNUAL BASE COST =  49920.00
   0 OF BASE LABOR CLASS AT ANNUAL COST =        0.


FACILITY = SECRA
CM COST =     755.24  PM COST =  33780.00  DM COST =  34535.24
COST OF CALLBACKS =        0.
   2 OF SITE LABOR CLASS  RAD          AT ANNUAL BASE COST =  49920.00
   0 OF BASE LABOR CLASS AT ANNUAL COST =        0.


FACILITY = CD
CM COST =     242.76  PM COST =  15510.00  DM COST =  15752.76
COST OF CALLBACKS =        0.
   1 OF SITE LABOR CLASS  RAD          AT ANNUAL BASE COST =  24960.00
   0 OF BASE LABOR CLASS AT ANNUAL COST =        0.


FACILITY = RMLT
CM COST =    3646.35  PM COST =  11340.00  DM COST =  14986.35
COST OF CALLBACKS =        0.
   1 OF SITE LABOR CLASS  RAD          AT ANNUAL BASE COST =  24960.00
   0 OF BASE LABOR CLASS AT ANNUAL COST =        0.
```

Figure 5-4. FMCM OUTPUT (PART A)

```
SUMMARY OF SECTOR VALUES
CM COST =  20424.41  PM COST = 337597.05  DM COST = 358021.46
COST OF CALLBACKS =   5432.94
   8 OF SITE LABOR CLASS  RAD          AT ANNUAL BASE COST = 199680.00
                 WITH ACTUAL PRODUCTIVITY =  .4433
   4 OF SITE LABOR CLASS  RAT          AT ANNUAL BASE COST =  99840.00
                 WITH ACTUAL PRODUCTIVITY =  .4347
  14 OF SITE LABOR CLASS  NAV          AT ANNUAL BASE COST = 349440.00
                 WITH ACTUAL PRODUCTIVITY =  .4179
   2 OF SITE LABOR CLASS  ENV          AT ANNUAL BASE COST =  29120.00
                 WITH ACTUAL PRODUCTIVITY =  .4334
   0 OF BASE LABOR CLASS AT ANNUAL COST =        0.
  17 OF MGT SUPPORT AT ANNUAL COST = 424320.00
 TOTAL SECTOR ANNUAL LABOR DIRECT COST = 782341.46
 TOTAL SECTOR ANNUAL LABOR BASE COST =1102400.00


 ALLOCATED FACILITY TYPE LABOR COST SUMMARY
  FACILITY QUANTITY   DIRECT LABOR COST      BASE LABOR COST
ASR               1             26078.05             36746.67
ARSR              1             26078.05             36746.67
SECRA             2             52156.10             73493.33
CD                1             26078.05             36746.67
RMLT              2             52156.10             73493.33
ARTS3             1             26078.05             36746.67
ALS               2             52156.10             73493.33
GS                4            104312.19            146986.67
LOC               5            130390.24            183733.33
LOM               4            104312.19            146986.67
MM                4            104312.19            146986.67
H                 1             26078.05             36746.67
VOR               1             26078.05             36746.67
TACAN             1             26078.05             36746.67

 DO YOU WANT TO RUN ANOTHER CASE? YES
```

Figure 5-5. FMCM OUTPUT (PART B)

```
INPUT SECTOR FILE NAME ? LOGAN
DO YOU WANT TO CONSIDER ALL FACILITY TYPES ? NO
HOW MANY TYPES ? 2
FACILITY ? ASR
CM COST =     501.21  PM COST =  23535.00  DM COST =  24036.21
COST OF CALLBACKS =        0.
  2 OF SITE LABOR CLASS  RAD          AT ANNUAL BASE COST =  49920.00
  0 OF BASE LABOR CLASS AT ANNUAL COST =        0.
FACILITY ? TACAN
CM COST =     393.81  PM COST =  48757.50  DM COST =  49151.31
COST OF CALLBACKS =        0.
  3 OF SITE LABOR CLASS  NAV          AT ANNUAL BASE COST =  74880.00
  0 OF BASE LABOR CLASS AT ANNUAL COST =        0.


SUMMARY OF SECTOR VALUES
CM COST =     895.01  PM COST =  72292.50  DM COST =  73187.51
COST OF CALLBACKS =        0.
  4 OF SITE LABOR CLASS  RAD          AT ANNUAL BASE COST =  99840.00
               WITH ACTUAL PRODUCTIVITY =  .1955
  0 OF SITE LABOR CLASS  AXT          AT ANNUAL BASE COST =        0.
               WITH ACTUAL PRODUCTIVITY = 0.
  4 OF SITE LABOR CLASS  NAV          AT ANNUAL BASE COST =  99840.00
               WITH ACTUAL PRODUCTIVITY =  .3939
  0 OF SITE LABOR CLASS  ENV          AT ANNUAL BASE COST =        0.
               WITH ACTUAL PRODUCTIVITY = 0.
  0 OF BASE LABOR CLASS AT ANNUAL COST =        0.
  9 OF MGT SUPPORT AT ANNUAL COST = 199680.00
TOTAL SECTOR ANNUAL LABOR DIRECT COST = 272867.51
TOTAL SECTOR ANNUAL LABOR BASE COST = 399360.00


ALLOCATED FACILITY TYPE LABOR COST SUMMARY
 FACILITY QUANTITY   DIRECT LABOR COST     BASE LABOR COST
ASR             1            136433.76           199680.00
TACAN           1            136433.76           199680.00


DO YOU WANT TO RUN ANOTHER CASE? NO
```

Figure 5-6. FMCM OUTPUT (PART C)

The first output block of Figure 5-4, for the ASR, shows corrective, preventive, and direct maintenance costs per year. It can be seen that direct maintenance cost is the sum of the costs of corrective and preventive maintenance. Since the ASR is subject to level C maintenance, there are no call-back costs. Two men in labor category RAD were considered in the calculation, at combined annual salaries of $49,920. Since only on-site repair is conducted at Logan, the base (intermediate) labor category is null; therefore, the cost is zero. Base repair is in the model as a logisitic-support scenario option. After the ASR cost data are printed, the next facility to be evaluated, "ARSR", is identified. This cycle continues until all facilities in the sector file have been examined.

Figure 5-5 shows the summary output for the entire sector. It gives the total corrective, preventive, and direct maintenance costs for 14 facility types and, for those facilities which are restoration level B, the total cost of call-backs. The total basic salaries of the four labor classes are displayed, as well as their expected actual productivities. Productivity is defined as the ratio of actual maintenance time to total on-duty time.

The item denoted "total sector annual direct cost" is the sum of the direct maintenance cost and management/support cost. The item denoted "total sector annual labor base cost" is the sum of the annual base (salary) costs of four labor classes and management/support cost. It is assumed that management/support personnel productivity is unity.

The table in the lower portion of Figure 5-5 is a summary of allocated labor costs for the entire set of facilities. The basis for the allocation in this case is that the 30 facilities have equal weight. It is possible, of course, to allocate these costs by another weighting system.

Figure 5-6 displays the same kinds of data as Figures 5-4 and 5-5. The only difference is that in this run only two facilities have been selected (a program option): the ASR and TACAN, which must be identified by terminal inputs before each is evaluated.

5.6 APPLICATION OF THE FMCM

The model, as noted earlier, is structured to have a common file (FACFIL) containing data on all types of facilities maintained by the Airways and Facilities Division of the FAA that are common to all sectors, and a series of files each containing data peculiar to a specific maintenance sector (SECFIL). The principal uses of the model, therefore, are:

To evaluate specific sectors or selected facility types within specific sectors for their attendant expected annual maintenance labor (and management/support) personnel requirements, direct labor costs, and salary costs.

To determine the impact on the maintenance sector or on the facility-type baseline evaluations due to specific changes in reliability, maintainability, technical or support parameters, maintenance scenario, etc.

To conduct sensitivity analysis to determine the driving parameters and their associated ranges of impact.

Specific sector maintenance evaluations are handled through normal exercise of the program, with specific sectors and facility types to be evaluated being designated by terminal inputs. The model is structured to permit evaluation of successive sectors/facility types without the need to recompile each time.

Alternative maintenance scenario evaluations can be handled in two ways: through a permanent change to file data (or establishment of additional permanent files) or through the insertion of temporary program statements to modify the main program. Selecting between these approaches for a specific application will depend on the nature and extent of the changes. If they tend to be simple, then the temporary change to the main program approach is preferred; otherwise, the changes are better made as permanent changes to the affected files. (In this latter case, additional permanent file changes would again be required to restore them to their original condition once the evaluations were completed.)

The best means of accomplishing sensitivity analyses is to insert temporary changes to the main program and take advantage of the looping feature of the program. To illustrate, assume that the sensitivity to some parameter (PARM) is desired and that PARM is read from either the common or sector files. Following the read statement for PARM, we could then insert the following temporary statements:

```
PRINT,  * VARIATION FACTORS*,

READ, VARF

PARM = VARF * PARM.
```

Thus, each time PARM is read from the file, its value is modified by a terminal input for the modification factor, which, if repeated over the range of interest for the parameter, would then provide the resultant output sensitivity curves for PARM (e.g., VARF could go from 0.1 to 10).

The demonstration exercises, which will be described in Chapter Six, considered all three usages of the program, with the latter two types of usage being accomplished via temporary changes to the main program.

Table 5-4 summarizes the specific terminal responses required for normal exercise of the program. The responses for usages with temporary changes to the program will depend on the nature of the changes introduced and their formats. These will be illustrated in Chapter Six for the specific cases considered during the demonstration exercises. As shown in the table, program usage is extremely simple, with terminal inputs being needed only to specify what is to be evaluated (sector/facility) during a given terminal session. The set-up of the files whose specific contents and structure are described and presented in the program documentation for the Logan maintenance sector represents the only complex aspect of program preparation.

Table 5-4. SUMMARY OF TERMINAL RESPONSE REQUIREMENTS FOR NORMAL PROGRAM EXECUTION

Question	Terminal Response	FORTRAN Variable	Comments
1. Input sector file name?	Permanent file name of sector to be evaluated, e.,g., LOGAN	SECFIL	None
2. Do you want to consider all facility types?	YES or NO	AA	None
3. How many types?	Integer number	NFT	Only if AA = YES.
4. Facility?	Facility name (e.g., ASR)	NAMF	Only if AA = YES.
5. Do you want to run another case?	YES or NO	AB	If AB = NO, programs stops; otherwise, it recycles to question 1 for a new case.

CHAPTER SIX

FMCM DEMONSTRATION

6.1 PURPOSE OF FMCM DEMONSTRATION

To show that the Facilities Maintenance Cost Model (FMCM) achieved the objectives for which it was developed and to illustrate how it could be utilized by TSC/FAA, an FMCM demonstration was performed. Using input file data provided by TSC, this demonstration showed the basic evaluation capability of the model and illustrated how the model could be applied in several representative parameter-variation cases defined by TSC.

Correspondingly, the model was exercised for a base case comprising 14 facility types within the Logan Maintenance Sector and a series of 15 parameter variations involving selected facility types within the sector. The specific demonstration exercises are summarized in Table 6-1. The methodology employed in obtaining these demonstration exercises is described in Section 6.2, and the results obtained from these exercises are presented in Section 6.3. The chapter concludes in Section 6.4 with comments concerning the specific results obtained and further types of applications that could be considered for the FMCM.

6.2 FMCM DEMONSTRATION METHODOLOGY

In order to demonstrate the utility of the FMCM, a representative set of data was generated for the Boston Airway Facility Maintenance Sector.

The Facilities Data File (FACFIL) presented in Figure 6-1 contains estimates of corrective and preventive maintenance parameters for a group of facilities assigned to the Boston Sector whose availability has an impact on aircraft delays. The mnemonic codes for the FACFIL are defined in Table 5-3. Corrective maintenance parameters such as MTBCMA, FITT, and MTTR, and preventive maintenance man-hours (PMMH) were obtained for each facility type from estimates made by Boston Sector personnel responsible for maintaining them. Other parameters, such as personnel sufficiency factor (SUF), MTTR, and BMMH, were set equal to zero to reflect current airway facilities maintenance practices.

Table 6-1. SUMMARY OF FMCM DEMONSTRATION EXERCISES

Run Number	Facility Types Exercised	Facilities with Parameter Variations	Nature of Run	Parameters Varied	New Parameter Values
1	ASR, ARSR, SECRA, CD, RMLT, ARTS-3, ALS, GS, LOC, LOM, M, H, VOR, TACAN	NA	Baseline case evaluations	NA	NA
2	ASR, TACAN	NA	Demonstrate selective facility evaluation feature	NA	NA
3	Same as Run 1 (All)	ASR	Change PM schedule	PMMH*	0, 0, 15, 8, 15, 26, 0, 0, 2, 6
4	All	ASR	Change PM schedule	PMMH*	0, 0, 21, 8, 15, 26, 0, 0, 2, 0
5	All	ASR	Change reliability	MTBCMA	225
6	All	ASR	Change reliability	MTBCMA	1100
7	All	ASR	Change to restoration level B	NRL NDS NWS PCOMB TRTP	0, 1, 0 0, 1, 0 0, 1, 0 0.95 2
8	All	ARTS-3	Change PM schedule	PMMH*	0, 0, 18, 25, 7, 1, 0, 8, 0, 7
9	All	ARTS-3	Change PM schedule	PMMH*	0, 0, 25, 25, 7, 1, 0, 0, 8, 0
10	All	ARTS-3	Change reliability	MTBCMA	4300
11	All	ARTS-3	Change reliability	MTBCMA	2190
12	All	ARTS-3	Change maintainability	FITT	4
13	All	ARTS-3	Change maintainability	FITT	2
14	All	ARTS-3	Change to restoration level B	NRL NDS NWS PCONB TRTP	0, 1, 0 0, 1, 0 0, 1, 0 0.5 2
15	All	LOC	Change reliability	MTBCMA	340
16	All	LOC	Change reliability	MTBCMA	680
17	All	LOC	Change to restoration level B	NRL NDS NWS PCONB TRTP	0, 5, 0 0, 1, 0 0, 1, 0 0.95 2

*PMMH is a vector. See Note 2 in Table 5-[illegible].

Line 20 in Figure 6-1 identifies the first set of data as that associated with the Glide Slope facility (GS). Lines 30 and 40 contain the data for the maintenance parameters defined in Table 5-3, as applicable to each Glide Slope facility in the Boston Sector. In the remaining lines of the file, the maintenance parameters are further abbreviated to single letters. For example, in line 60, "M 170" represents an MTBCMA of 170 hours for the Localizer (LOC) facility type. The other facility types contained in the file are:

LOM - Compass Locator/ILS Outer Marker

MM - ILS Middle Marker

H - Nondirectional Radio Beacon

VOR - VHF Omnidirectional Range

TACAN - Tactical Air Navigation

ASR - Airport Surveillance Radar

ARSR - Air Route Surveillance Radar

SECRA - Secondary Radar Beacon

CD - Common Digitizer

ARTS-3 - Automated Radar Terminal System

ALS - Approach Light System

RMLT - Radar Microwave Link Terminal.

The Sector Data File (SECFIL), presented in Figure 6-2 for the Boston (Logan) Sector, contains sector-peculiar data defined in Table 5-1. Lines 30, 40, 50, and 60 contain labor rates for maintenance technicians assigned to radar computer, navigation/linking aid, and environmental facility types, respectively. Refacility types identified in lines 80, 120, 160, etc., are identical to those contained in the FACFIL. The data used were once again obtained from Boston Sector personnel responsible for maintenance operations.

6.3 PRESENTATION OF DEMONSTRATION RESULTS

As noted in Table 6-1 parameter variations were made for the ASR, ARTS-3, and LOC facility types. Tables 6-2 through 6-4 present the results obtained from these exercises, along with the corresponding baseline-case evaluations. Intermediate-level repair personnel levels and costs are not included in these tables since this option was not considered for the demonstration exercises and hence these values would be zero in every case. The terminal output originals from these demonstration exercises were transmitted directly to the project Contract Officer's Technical Representative (COTR) at TSC immediately following completion of the exercises.

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USER DELAY COST MODEL AND FACILITIES MAINTENANCE COST MODEL FOR--ETC(U)
MAY 78 L B GREENE, J WITT DOT-TSC-1173-1

UNCLASSIFIED FAA-AAF-220-78-01-1 NL

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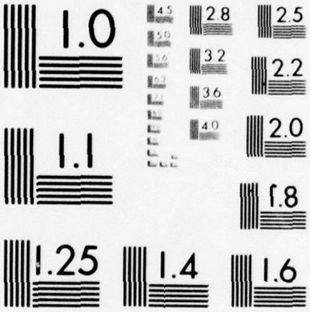

MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

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```
10 FACILITIES DATA FILE
20 GS
30 MTBCMA 8760. SUF 0. FITT 6. MTTR 2. MTRR 0. BMMH 0.
40 PMMH 0. 1. 4. 4. 1. 1. .25 0. .5 0.
50 LOC
60 M 170. S 0. F .1 M .3 M 0. B 0.
70 P 0. 8. 4. 4. 16. 2. 0. .25 .5 0.
80 LOM
90 M 8760. S 0. F .7 M .3 M 0. B 0.
100 P 0. 0. .25 1. 0. 1. 0. 0. 0. 1.
110 MM
120 M 8760. S 0. F .7 M .3 M 0. B 0.
130 P 0. 0. .25 1. 0. 1. 0. 0. 0. 1.
140 H
150 M 25000. S 0. F 10. M .3 M 0. B 0.
160 P 0. 0. 0. 0. 0. .25 0. 0. 0. 1.
170 VOR
180 M 340. S 0. F .25 M 12. M 0. B 0.
190 P 0. 1. 6. 5. 1. 0. 0. 0. 0. 0.
200 TACAN
210 M 500. S 0. F .5 M .5 M 0. B 0.
220 P 8. 4. 8. 0. 0. 2. 0. 0. 0. 0.
230 ASR
240 M 550. S 0. F .5 M .5 M 0. B 0.
250 P 2. 6. 15. 8. 15. 26. 0. 0. 0. 0.
260 ARSR
270 M 730. S 0. F 1.5 M .5 M 0. B 0.
280 P 3. 3. 8. 10. 6. 2. 0. 0. 0. 0.
290 SECRA
300 M 730. S 0. F .5 M 1. M 0. B 0.
310 P 1. 8. 15. 0. 6. 0. 0. 0. 0. 0.
320 CD
330 M 8760. S 0. F 16. M .2 M 0. B 0.
340 P 2. 2.5 7. 11. 16. 4. 0. 0. 0. 0.
350 ARTS3
360 M 8760. S 0. F 8. M 2. M 0. B 0.
370 P 8. 7. 18. 25. 7. 1. 0. 0. 0. 0.
380 ALS
390 M 365. S 0. F .5 M 2. M 0. B 0.
400 P 0. 7. 4. 0. 10. 400. 0. 0. 0. 0.
410 RMLT
420 M 180. S 0. F .5 M 2. M 0. B 0.
430 P 0. 2. 9. 40. 2. 2. 0. 0. 0. 0.
```

Figure 6-1. **FACILITY FILE**

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```
10 LOGAN SECTOR DATA FILE
20 NFT 14 NSL 4 MLR 12. BLR 0. PRUDR .7
30 RAD SLR 12. PSLR 18. SDIF 1.25
40 APT SLR 12. PSLR 18. SDIF 1.25
50 NAV SLR 12. PSLR 18. SDIF 1.25
60 ENV SLR 12. PSLR 10.5 SDIF 1.25
70 MPSR 0 0 0 0 3 4 5 8 9 10 11 12 13 15 17 19 21 23 25 27 29 31
80 ASR
90 AOH 8760. DOH 24. PCONR 0. RTS 1. PROD .6 NSCAT 2
100 NPLH 0 NDSH 0 NWSH 0 NPLB 0 NDSB 0 NWSB 0 NPLC 1 NDSC 3 NWSC 3
110 TRTP 0. TRT .3 TRTD .3
120 ARSR
130 AOH 8760. D 24. P 0. R 1. P .6 N 2
140 N 0 N 0 N 0 N 0 N 0 N 0 N 1 N 3 N 3
150 T 0. T 0. T 0.
160 SECRA
170 AOH 8760. D 24. P 0. R 1. P .6 N 2
180 N 0 N 0 N 0 N 0 N 0 N 0 N 2 N 2 N 3
190 T 0. T .3 T .3
200 CD
210 AOH 8760. D 24. P 0. R 1. P .6 N 2
220 N 0 N 0 N 0 N 0 N 0 N 0 N 1 N 3 N 3
225 T 0. T 0. T 0.
240 RMLT
250 AOH 8760. D 24. P 0. R 1. P .6 N 2
260 N 0 N 0 N 0 N 0 N 0 N 0 N 2 N 3 N 3
270 T 0. T 0. T 0.
280 ARTS3
290 AOH 8760. D 24. P 0. R 1. P .6 N 4
300 N 0 N 0 N 0 N 0 N 0 N 0 N 1 N 3 N 3
310 T 0. T 0. T 0.
320 ALS
330 AOH 4380. D 12. P 0. R 1. P .6 N 4
340 N 0 N 0 N 0 N 3 N 2 N 2 N 0 N 0 N 0
350 T 0. T .25 T 0.
360 GS
370 AOH 8760. D 24. P .95 R 1. P .6 N 3
380 N 0 N 0 N 0 N 1 N 1 N 1 N 3 N 3 N 3
390 T 2. T .25 T .25
400 LOC
410 AOH 8760. D 24. P .95 R 1. P .6 N 3
420 N 0 N 0 N 0 N 2 N 1 N 1 N 3 N 3 N 3
430 T 2. T .3 T .3
440 LOM
450 AOH 8760. D 24. P .95 R 1. P .6 N 3
460 N 0 N 0 N 0 N 1 N 1 N 1 N 3 N 3 N 3
470 T 2. T 1. T 0.
480 MM
490 AOH 8760. D 24. P .95 R 1. P .6 N 3
500 N 0 N 0 N 0 N 1 N 1 N 1 N 3 N 3 N 3
510 T 2. T 1. T 0.
520 H
530 AOH 8760. D 24. P 0. R 1. P .6 N 3
540 N 0 N 0 N 0 N 0 N 0 N 0 N 1 N 3 N 3
550 T 0. T .3 T 0.
560 VOR
570 AOH 8760. D 24. P 0. R 1. P .6 N 3
580 N 0 N 0 N 0 N 0 N 0 N 0 N 1 N 3 N 3
590 T 0. T .25 T 0.
600 TACAN
610 AOH 8760. D 24. P 0. R 1. P .6 N 3
620 N 0 N 0 N 0 N 0 N 0 N 0 N 1 N 3 N 3
630 T 0. T .25 T 0.
```

Figure 6-2. LOGAN SECTOR FILE

Table 6-2. SUMMARY OF ASR VARIATION RESULTS

Output Cost Factor	Results					
	Run 1*	Run 3	Run 4	Run 5	Run 6	Run 7
ASR CM Cost**	501.21	501.21	501.21	1,002.42	250.60	1,146.15
ASR PM Cost**	23,535.00	10,821.00	9,327.00	23,535.00	23,535.00	18,828.00
ASR DM Cost**	24,036.21	11,322.21	9,828.21	24,537.42	23,785.00	19,974.18
ASR Call-Back Cost**	0.00	0.00	0.00	0.00	0.00	999.14
ASR Type Labor	RAD	RAD	RAD	RAD	RAD	RAD
Number of ASR Site Personnel	2	1	1	2	2	2
ASR Type Labor Sector Salary	49,920.00	24,960.00	24,960.00	49,920.00	49,920.00	49,920.00
CM Cost**	20,424.41	20,424.41	20,424.41	20,925.62	20,173.81	21,069.39
Sector PM Cost**	337,597.05	324,883.05	323,399.05	337,597.05	337,597.05	332,890.05
Sector DM Cost**	358,021.46	345,307.46	343,813.46	358,522.67	357,770.86	353,959.44
Sector Call-Back Cost**	5,422.94	5,422.94	5,422.94	5,422.94	5,422.94	6,422.08
Number of RAD Technicians Within Sector	8	7	7	8	8	8
Sector Type Labor Salary	199,680.00	174,720.00	174,720.00	199,680.00	199,680.00	199,680.00
Sector Type Labor Productivity	0.4433	0.4484	0.4415	0.4453	0.4423	0.4420
Number of Management Personnel Within Sector	17	17	17	17	17	17
Sector Management Support Salary	424,320.00	424,320.00	424,320.00	424,320.00	424,320.00	424,320.00
Sector Total Labor Cost**	782,341.46	769.627.46	768,133.46	782,842.67	782,090.86	778,279.44
Sector Total Salary	1,102,400.00	1,077,440.00	1,077,440.00	1,102,400.00	1,102,400.00	1,102,400.00

*As defined by Table 6-1.
**Dollars per year.

Table 6-3. SUMMARY OF ARTS-3 VARIATION RESULTS

Output Cost Factor	Results							
	Run 1*	Run 8	Run 9	Run 10	Run 11	Run 12	Run 13	Run 14
ARTS-3 CM Cost**	149.85	149.85	149.85	299.70	559.40	89.91	59.94	164.02
ARTS-3 PM Cost**	54,105.00	29,535.00	18,705.00	54,105.00	54,105.00	54,105.00	54,105.00	43,284.00
ARTS-3 DM Cost**	54,254.85	29,684.85	18,854.85	54,404.70	54,704.40	54,194.91	54,164.94	43,448.02
ARTS-3 Call-Back Cost**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	84.04
ARTS-3 Type Labor	ART	ART	ART	ART	ART	ART	ART	ART
Number of ARTS-3 Site Personnel	3	2	2	3	3	3	3	3
ARTS-3 Type Labor Salary	74,880.00	49,920.00	49,920.00	74,880.00	74,880.00	74,880.00	74,880.00	74,880.00
Sector CM Cost**	20,424.41	20,424,41	20,424.41	20,574.26	20,873.96	20,364.47	20,334.50	20,433.58
Sector PM Cost**	337,597.05	313,027.05	302,197.05	337,597.05	337,597.05	337,597.05	337,597.05	326,776.05
Sector DM Cost**	358,021.46	333,451.46	322,621.46	358,171.31	358,471.01	357,961.52	357,931.55	347,214.63
Sector Call-Back Cost**	5,422.94	5,422.94	5,422.94	5,422.94	5,422.94	5,422.94	5,422.94	5,506.98
Number of ART Technicians Within Sector	4	4	4	4	4	4	4	3
Sector Type Labor Salary	99,840.00	99,840.00	99,840.00	99,840.00	99,840.00	99,840.00	99,840.00	74,880.00
Sector Type Labor Productivity	0.4347	0.2379	0.1511	0.4359	0.4383	0.4343	0.4340	0.5791
Number of Management Personnel Within Sector	17	17	17	17	17	17	17	17
Sector Management Support Salary	424,320.00	424,320.00	424,320.00	424,320.00	424,320.00	424,320.00	424,320.00	424,320.00
Sector Total Labor Cost**	782,341.46	757,771.46	746,941.46	782,491.31	782,791.01	782,281.52	782,251.55	771,534.63
Sector Total Salary	1,102,400.00	1,102,400.00	1,102,400.00	1,102,400.00	1,102,400.00	1,102,400.00	1,102,400.00	1,077,440.00

*As defined by Table 6-1.
**Dollars per year.

Table 6-4. SUMMARY OF LOC VARIATION RESULTS

Output Cost Factor	Results			
	Run 1*	Run 15	Run 16	Run 17
LOC CM Cost**	7,941.59	3,970.79	1,985.40	14,062.71
LOC PM Cost**	39,033.30	39,033.30	39,033.30	33,942.00
LOC DM Cost**	46,974.89	43,004.09	41,018.70	48,004.71
LOC Call-Back Cost**	5,172.02	2,586.01	1,293.00	12,930.04
LOC Type Labor	NAV	NAV	NAV	NAV
Number of LOC Site Personnel	3	3	3	3
LOC Type Labor Salary	74,880.00	74,800.00	74,800.00	74,800.00
Sector CM Cost**	20,424.41	16,453.62	14,468.22	26,545.53
Sector PM Cost**	337,597.05	337,597.05	337,597.05	332,505.75
Sector DM Cost**	358,021.46	354,050.67	352,065.27	359,051.28
Number of NAV Technicians Within Sector	14	14	14	14
Sector Type Labor Salary	349,440.00	349,440.00	349,440.00	349,440.00
Sector Type Labor Productivity	0.4179	0.4146	0.4130	0.4146
Number of Management Personnel Within Sector	17	17	17	17
Sector Management Support Salary	424,320.00	424,320.00	424,320.00	424,320.00
Sector Total Labor Cost**	782,341.46	778,370.67	776,385.27	783,371.28
Sector Total Salary	1,102,400.00	1,102,400.00	1,102,400.00	1,102,400.00

*As defined by Table 6-1.

**Dollars per year.

6.4 DISCUSSION OF DEMONSTRATION RESULTS

The objectives of the demonstration exercises, as discussed previously, were (1) to demonstrate the operation of the FMCM in its baseline and parameter-variation modes, and (2) to obtain actual evaluations of cases of interest. Both of the objectives were achieved by these exercises.

As shown in the top line of Figure 5-5, the baseline case evaluation of the Logan Sector showed a direct maintenance cost per year of $358,021.46 (5.7 percent CM, 94.3 percent PM), of which $5,422.94 (1.5 percent) was due to restoration level B call-back costs. This direct labor demand translated into a sector maintenance-force requirement of 23, spread over four labor skills (RAD, ART, NAV, ENV) and with an associated annual salary of $678,080. It was determined by table look-up that a total of 17 management/support personnel would be necessary for this size labor force, with an associated salary cost of $424,320.00. Thus the total annual salary for the Logan sector was determined to be $1,102,400.00, with a corresponding average productivity (assuming management/support 100 percent productive) of 71 percent. Average productivity is defined as total annual labor direct cost ($782,341.40) divided by total annual sector base cost ($1,102,400.00). It should be noted that when the effects of the management/support personnel and call-backs are removed, the productivity (of maintenance personnel) drops to 52 percent.

Three facility types were evaluated during the parameter variation exercises (ASR, ARTS-3, and LOC). The parameters varied are shown in Table 6-5. Table 6-6 summarizes the resultant "best choice" among the options considered for each facility type in terms of its net impact (from the baseline values) on the sector costs. The last column in the table represents the cumulative potential savings across all three facility types. "Best choice" in this case represents the option that results in the minimum total salary for the sector or the minimum direct labor costs for the sector. These results show a potential labor cost saving of $30,961.02, with a possible force reduction of 2 and a corresponding potential salary savings of $49,920.00. It is also interesting to note that the specific "best choice" option was different in each case; i.e., for the ASR, it was a PM frequency change; for ARTS-3, it was a restoration level change; and for LOC, it was a change in the maintainability (FITT).

As demonstrated, the FMCM provides a potentially useful tool to the FAA/TSC that can be easily applied to evaluate a large number of potential approaches toward reducing the cost of maintenance within the Airways and Facilities System. When used in conjunction with the User Delay Cost Model, it provides a readily accessible means of linking the potential cost savings through changes in the maintenance system to the corresponding impacts on the using community. It thus enables determination of the overall best options to the FAA and the user community in terms of possible changes to the Airways and Facilities Maintenance System.

Table 6-5. SUMMARY AND VARIATION EXERCISES: TERMINAL INPUTS

Question	Terminal Response	FORTRAN Variable	Comments
Sector file name?	LOGAN	SECFIL	None
Facility?	Facility type affected (e.g., ARTS-3)	NVARF	None
Consider all types?	YES	AA	None
Parameter?	1,2,3, or 4	NPAR	1 = PMMH Variation 2 = MTBCMA Variation 3 = Restoration Level Variation 4 = FITT Variation
Factor?	Positive real variable	XFAC	When NPAR = 2 or 4
PMMH?	10 positive real variables	PMMH(IJ)	When NPAR = 1
NRL?	3 integer variables	NRL(IJ)	When NPAR = 3
NDS?	3 integer variables (1,2, or 3)	NDS(IJ)	When NPAR = 3
NWS?	3 integer variables (0,1,2, or 3)	NWS(IJ)	When NPAR = 3
Another case?	YES or NO	AB	None

Table 6-6. SUMMARY OF BEST-CHOICE RESULTS FROM DEMONSTRATION EXERCISES

Facility Type	Results			
	ASR	ARTS-3	LOC	Composite
Best-Choice Run	4	14	16	
Δ-Sector CM Cost*	0.00	(14.17)	5,956.19	5,942.02
Δ-Sector PM Cost*	14,208.00	10,821.00	0.00	25,019.00
Δ-Sector DM Cost*	14,208.00	10,806.83	6,956.19	31,971.02
Δ-Sector Call-Back Cost*	0.00	(84.04)	3,879.01	3,794.97
Δ-Sector Maintenance Personnel	1(RAD)	1(ART)	0(NAV)	2
Δ-Sector Maintenance Salary	24,960.00	24,960.00	0.00	49,920.00
Δ-Sector Management/Support Personnel	0	0	0	0
Δ-Sector Management/Support Salary	0.00	0.00	0.00	0.00
Δ-Sector Total Labor Cost*	14,208.00	10,806.83	5,956.83	30,971.66
Δ-Sector Total Salary	24,960.00	24,960.00	0.00	49,920.00

*Dollars per year.

CHAPTER SEVEN

CONCLUSIONS AND RECOMMENDATIONS

The principal conclusions and recommendations derived from this study are presented in this chapter.

7.1 CONCLUSIONS

On the basis of the analysis of the model demonstration results, as reported in Chapters Four and Six of this report, the following conclusions are made:

The UDCM is an effective tool for evaluating the effects of several factors on user delays.

While the UDCM was designed to evaluate delays induced by facility outages, it has been shown to demonstrate the effects of a number of factors other than facility outage -- e.g., aircraft schedule intensity, weather -- and is therefore a powerful analytic tool having potential utility in a wide range of FAA/TSC planning and management decisions.

The FMCM was demonstrated to be responsive to variation in maintenance strategies and can easily be applied to evaluate a large number of potential approaches to maintenance-cost reduction within the Airways and Facilities System.

7.2 RECOMMENDATIONS

The conclusions support the following ARINC Research Corporation recommendations for future development:

Expand, refine, and validate the UDCM. Areas of expansion include enlarging the model to remove some of the limitations -- e.g., enabling the model to simulate movement of aircraft to and from secondary airports. Considerable emphasis has been given to the lack of an authoritative input base, particularly of data related to aircraft generation. A thorough data collection effort should be made before the model is validated and exercised. Once a good data base has been obtained, the model should be validated. This would require exercising the model with good input data and comparing model outputs with similar delay measures observed at Logan under comparable conditions.

Expand, refine, and validate the FMCM. Included in this recommendation are the following requirements: expand the model capability to cover combinations of sectors and enlarge it to include maintenance costs other than labor. Model validation would involve comparing model outputs with actual maintenance costs encountered when scenarios similar to those modeled are used.

Develop and implement the Facility Availability Model as a joint analysis tool with the UDCM and FMCM. When this is done, it will be possible to identify levels of availability that are optimal, or near optimal, with respect to the criterion of costs to the FAA and the using community.

Develop a Maintenance Management Information system. The implementation of this recommendation would not only support the maintenance management function but would also provide an ongoing source of valid data for the analysis and selection of optimal logistics scenarios through the exercise of the three models.

Acquire cost factors for the conversion of delay measures to current dollar figures.

7.3 SUMMARY

The objectives of the study have been successfully met. The two models have been demonstrated, and they perform as desired and expected. ARINC Research Corporation believes that a methodology has been identified and proven feasible that can and should be further exploited.

APPENDIX A

REQUIRED UDCM INPUT DATA

This appendix describes and discusses the nature of the data required by the UDCM. The numerical quantities presented herein are those used in the model as it was configured for demonstration. Annotated sample input matrices are included. A complete listing of the input data matrices is included in the program print-out in the model documentation.

1. WEATHER DATA

Figure A-1 provides a sample of how weather data was received from the National Climatic Survey. This figure shows weather conditions during daylight hours with the wind from the north. The study used 32 such tables corresponding to all 16 points of the compass for day and night.

Table A-1 is derived from Figure A-1. The derivation was performed manually and displays ceiling frequencies as a function of wind direction and velocity. For example, summing over the columns of Figure A-1 for a wind speed of 10 to 14 knots, under ceiling category 1000+, gives a frequency of 103 observations. This figure is displayed in the first row, third column of Table A-1. The same procedure is repeated for all entries in Table A-1.

Table A-2 is also derived from Figure A-1. Given the ceiling of approximately 1000 feet, a total of 314 observations occur, as can be seen in row 6 labeled "TOT", and the last column labeled "TOT OPS". Of these, 309 occurred when the visibility was 3+, 1 when the ceiling was 1-3/4 to 2-1/2 nautical miles, and so on. These data were converted to cumulative percentages, expressed as numbers 000 to 999, for computer utilization. Figure A-2 shows an example of such a table, expressed as a matrix, as printed out in a program run.

The top matrix in this figure is first used to find the wind direction, or whether it is calm. Column 1 displays 17 entries, row 1 representing a calm condition, and each of the others one of the 16 points of the compass. Columns 2 and 3 contain cumulative percentages of occurrences for each of these conditions -- column 3 for daylight hours, column 2 for night. A uniform random variable, U, is drawn from the unit interval and compared with the numbers in column 2 or 3. For example, assume daylight hours,

		CEILING GROUPS IN FEET	VEL GROUPS M.P.H.	VISIBILITY GROUPS IN MILES							
STA	DIR			0-1/4	5/16-1/2	5/8-7/8	1	1 1/4-1 1/2	1 3/4-2 1/2	3+	TOT OBS
14739	N	1000+	1-4					1		21	22
			5-9				1			131	132
			10-14				1	1	1	100	103
			15-29							57	57
			30+								
			TOT				2	2	1	309	314
		600-900	1-4							2	2
			5-9		1		1	1	2	6	11
			10-14		1	1			1	15	18
			15-29		1		2	2	1	10	16
			30+							3	3
			TOT		3	1	3	3	4	36	50
		500	1-4							1	1
			5-9				1		1	3	5
			10-14							3	3
			15-29		1	1		2	1	3	8
			30+								
			TOT		1	1	1	2	2	10	17
		400	1-4					1			1
			5-9						1	1	2
			10-14	1	1				2	3	7
			15-29							3	3
			30+							1	1
			TOT	1	1			1	3	8	14
		300	1-4							1	1
			5-9				3			1	4
			10-14					2		3	5
			15-29			1		1		2	4
			30+								
			TOT			1	3	3		7	14
		200	1-4		1				1		2
			5-9								
			10-14					1			1
			15-29								
			30+								
			TOT		1			1	1		3
14739	N	0-100	1-4	1							1
			5-9		1	1	1				3
			10-14								
			15-29	1							1
			30+								
			TOT	2	1	1	1				5
		TOT VIS		3	7	4	10	12	11	370	417
		VEL GRPS			1-4	5-9	10-14	15-29	30+	CALM	
		TOT VEL			30	157	137	89	4		417
		% VEL			7.2	37.6	32.9	21.3	1.0		100.0
		% DIR									5.7

Figure A-1. SAMPLE OF NATIONAL CLIMATIC SURVEY WEATHER DATA

Table A-1. FREQUENCY OF OCCURRENCE OF CEILING, GIVEN WIND DIRECTION (NORTH), SPEED, AND DAYLIGHT HOURS

Ceiling (Feet)	Velocity (Knots)				
	1-4	5-9	10-14	15-29	30+
1000+	22	132	103	57	0
600-900	2	11	18	16	3
500	1	5	3	8	0
400	1	2	7	3	1
300	1	4	5	4	0
200	2	0	1	0	0
0-100	1	3	0	1	0
Total	30	157	137	89	4

Table A-2. FREQUENCY OF OCCURRENCE OF VISIBILITY, GIVEN CEILING, WIND DIRECTION (NORTH), AND DAYLIGHT HOURS

Visibility (Nautical Miles)	Ceiling (Feet)						
	1000+	600-900	500	400	300	200	0-100
0 to 1/4	0	0	0	1	0	0	2
5/16 to 1/2	0	3	1	1	0	1	1
5/8 to 7/8	0	1	1	0	1	0	1
1	2	3	1	0	3	0	1
1-1/4 to 1-1/2	2	3	2	1	3	1	0
1-3/4 to 2-1/2	1	4	2	3	0	1	0
3	309	36	10	8	7	0	0
Total	314	50	17	14	14	3	5

MATRIX HALFWORD SAVEVALUECIRVL

Wind Direction in Degrees

		NT	DY	NT	DY	NT	DY	NT	DY	NT	DY		
	COL. 1	2	3	4	5	6	7	8	9	10	11	12	13
												Ceiling Matrix	Visibility Matrix
Calm 1	360	7	1	1000	1000	1000	1000	1000	1000	1000	1000	2	3
N 2	0	96	58	61	7	576	448	839	777	1000	990	4	5
NNE 3	22	128	85	152	76	704	510	891	753	956	995	6	7
NE 4	45	163	118	113	29	510	324	755	639	981	979	8	9
ENE 5	67	198	169	82	441	494	0	724	770	981	992	10	11
E 6	90	232	263	167	49	642	437	776	820	976	996	12	13
ESE 7	112	254	348	207	47	671	0	866	804	994	1000	14	15
SE 8	135	272	398	237	66	777	680	935	962	993	995	16	17
SSE 9	157	296	425	153	101	736	641	939	924	1000	995	18	19
S 10	180	365	489	109	53	757	456	949	803	1000	985	20	21
SSW 11	202	424	550	58	20	569	211	845	602	1000	998	22	23
SW 12	225	496	591	48	17	479	195	779	510	998	1000	24	25
WSW 13	247	616	663	19	15	439	302	827	645	999	992	26	27
W 14	270	776	777	69	14	312	211	651	498	990	966	28	29
WNW 15	292	836	874	33	101	295	184	649	439	974	977	30	31
NW 16	315	937	958	26	20	396	225	734	554	996	993	32	33
NNW 17	337	1000	1000	30	13	413	835	835	658	1000	1000	34	35
18	0	0	0	0	0	0	0	0	0	0	0	0	0
	Wind direction in degrees	Number of cumulative occurrences, out of 1000, of wind direction in Day/Night		3 Knots		7 Knots		12 Knots		22 Knots		Default = 30 Knots	

Wind Velocity

MATRIX HALFWORD SAVEVALUE 4

	NT	DY	NT	DY	NT	DY	NT	DY	NT	DY
Ceiling	COL. 1	2	3	4	5	6	7	8	9	10
1000' 1	825	733	798	841	762	752	714	640	1000	0
750' 2	850	800	857	911	878	883	876	820	1000	750
500' 3	850	833	881	943	901	905	933	910	1000	750
400' 4	850	866	914	956	948	956	962	944	1000	1000
300' 5	875	900	950	981	977	992	991	989	1000	1000
200' 6	950	967	977	981	994	1000	1000	989	1000	1000
Default = 50'										
Wind Velocity	3 Knots		7 Knots		12 Knots		22 Knots		30 Knots	

Ceiling matrix for wind N

MATRIX HALFWORD SAVEVALUE 5

	NT	DY	NT	DY	NT	DY	NT	DY	NT	DY	NT	DY	NT	DY
Visibility in Miles	COL. 1	2	3	4	5	6	7	8	9	10	11	12	13	14
.25 1	0	0	0	0	0	0	0	71	0	0	63	0	455	400
.50 2	2	0	0	60	0	59	0	143	0	0	313	333	728	600
.80 3	2	0	17	80	56	118	91	143	48	71	501	333	819	800
1.00 4	6	6	51	120	111	176	136	143	238	286	564	333	910	1000
1.50 5	6	13	85	200	222	294	227	214	381	500	814	667	910	1000
2.00 6	12	16	171	260	389	412	485	429	810	500	877	1000	1000	1000
Default = 3.00														
Ceiling	1000'		750'		500'		400'		300'		200'		50'	

Visibility matrix for wind N

Figure A-2. SAMPLE OF WEATHER MATRIX INPUTS and let the number drawn be .045, or equivalently 045 and, thus, since $045 \leqslant 058$ (row 2, column 3), the wind is from the north. To determine wind speed, another U is drawn and compared with the odd-numbered column elements in row 2. If $U = 720$, and $448 < 720 \leqslant 777$ (where 448 is in row 2, column 7 and 777 is in row 2, column 9) the wind speed is 12 knots.

To determine ceiling, columns 12 and 13 identify the ceiling and visibility matrices for each wind direction and matrix 4 (the middle table of the figure) is used for ceiling determination with a north wind. Column 6 corresponding to a speed of 12 knots, daylight, is entered with another value of U, for example 921. Since $905 < 921 \leqslant 956$, the ceiling is 400 feet.

When the ceiling is determined, matrix 5 (the last table in the figure) is used to find the visibility. A new U is obtained and compared with the entries in column 8, which corresponds to a 400-foot ceiling, north wind, daylight hours. If $U = 415$, and $214 < 415 \leqslant 429$, the visibility is 2 miles.

There is no row in the wind direction, ceiling, and visibility matrices corresponding to 30 knots, 50 feet, and 3 miles, respectively. These are defaults which, if U is greater than any number in the column, the value associated with these quantities is assigned. The tabulated values of wind direction and speed, ceiling and visibility are thus found and treated by the computer as nominal values to which, within their respective ranges of values, a random uniform increment is added or subtracted. As mentioned in Section 3.3.1 of Chapter Three, between wind changes, ceiling and visibility are allowed to fluctuate randomly within their ranges by an exponential process with a mean time to change of 15 minutes.

2. ARRIVAL RATES

The arrival rate data were not collected in the form discussed; that is, arrival rates for both weather conditions at all destination airports by time of day are not known. Were these available, the overall arrival rate for any hour, both VFR and IFR, could be found by summing λ_{ijk} over i — the destination airports. An approximation was used in the model demonstration. The source for this approximation was data from the Performance Measurement System (PMS) for Airports, dated November 1975. Figure A-3 was taken from this report and shows arrivals of scheduled aircraft as a function of time. This graph was converted, by manual measurement, into a table of approximate numbers. The table was extended quite arbitrarily to cover a 24-hour day. It was assumed that these rates could be made applicable to IFR or VFR conditions by multiplying them by a constant. This, in fact, was done in the demonstration runs. In other words, at present, these data are not authoritative. The last column in Figure A-4 shows the rate of arrival, by time of day, for VFR conditions. These figures are the same as those used in the demonstration at TSC on September 20-22, 1976. Other uses of the matrix in Figure A-4 are discussed in the following section. It is suggested that before the model is exercised for analysis that these data be collected in the form called for in the previous discussions. Assuming the total arrival rates for weather conditions and time of day for each destination airport were available, the model could be expected to simulate accurately the phenomenon of arrival time creation.

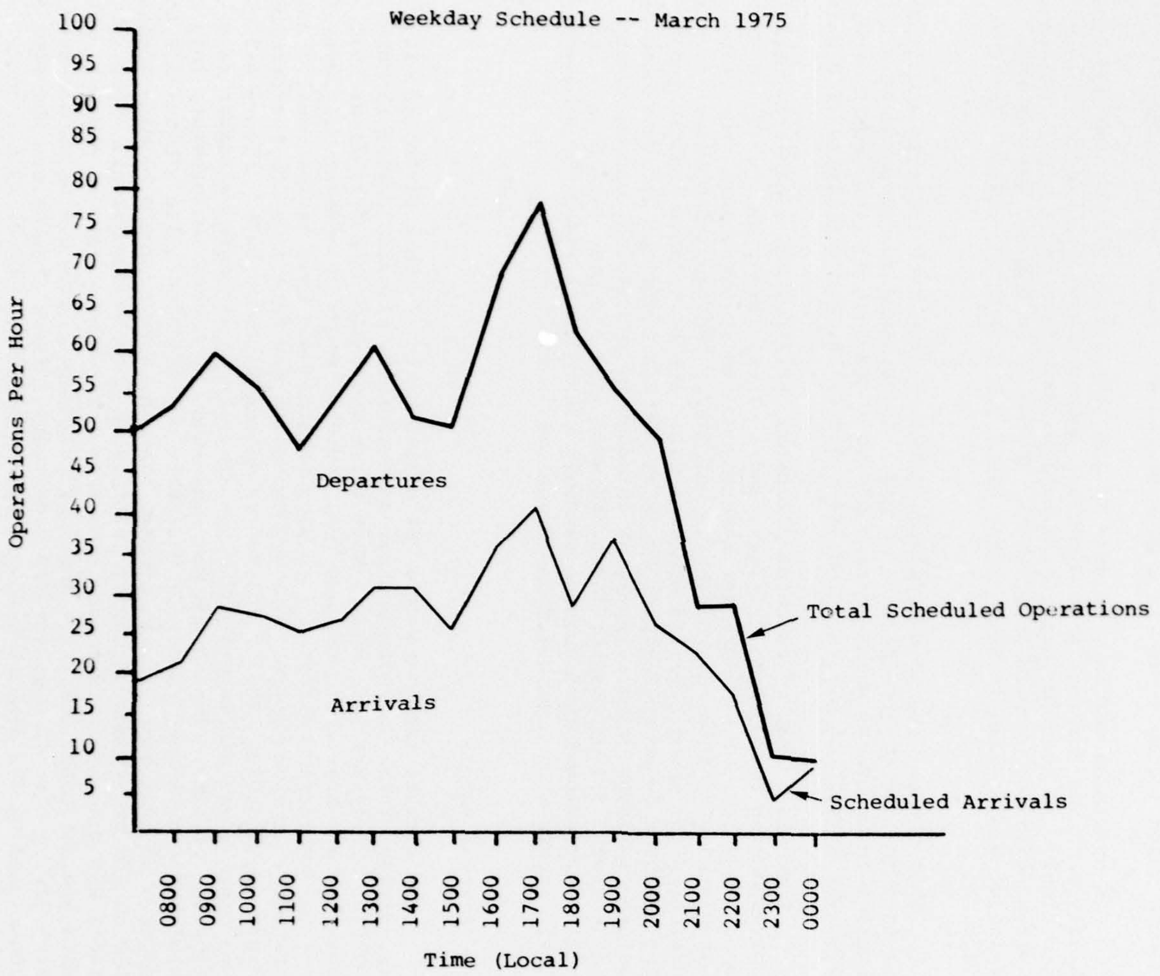


Figure A-3. SCHEDULED ARRIVAL RATE AT LOGAN

```
MATRIX HALFWORD SAVEVALUEVFRAC                                          Secondary Airports
              ---------Hold Areas---------
          COL. 1     2     3     4     5     6     7     8     9    10    11    12    13    14    15    16    17     18  Default to Tew Mac

     ROW  1    297   597   847   897   996   996   996   996   997   997   997   997   997   997   997  1000  1000     7
          2    299   598   847   897   996   996   996   996   997   997   997   997   997   997   997  1000  1000     6
          3    299   598   847   897   996   996   996   996   997   997   997   997   997   997   997  1000  1000     5
          4    299   598   847   897   996   996   996   996   997   997   997   997   997   997   997  1000  1000     8
          5    299   598   847   897   996   996   996   996   997   997   997   997   997   997   997  1000  1000    11
          6    299   598   847   897   996   996   996   996   997   997   997   997   997   997   997  1000  1000    17
          7    299   598   847   897   996   996   996   996   997   997   997   997   997   997   997  1000  1000    25
          8    260   522   740   784   871   871   871   954   955   955   955   955   955   998   998  1000  1000    30
          9    251   502   711   752   836   929   946   947   948   954   954   955   955   996   997   998   999    41
         10    251   502   710   752   836   928   946   947   948   954   955   955   955   996   997   998   999    40
         11    251   502   710   752   836   928   946   947   948   954   955   955   955   996   997   998   999    39
 Time of 12    251   502   710   752   836   928   946   947   948   954   955   955   955   996   997   998   999    40  Number of aircraft
   Day   13    251   502   710   752   836   928   946   947   948   954   955   955   955   996   997   998   999    46  created in VFR
         14    251   502   710   752   836   928   946   947   948   954   955   955   955   996   997   998   999    46  conditions
         15    251   502   710   752   836   928   946   947   948   954   955   955   955   996   997   998   999    40
         16    251   502   710   752   836   928   946   947   948   954   955   955   955   996   997   998   999    53
         17    251   502   710   752   836   928   946   947   948   954   955   955   955   996   997   998   999    60
         18    251   502   710   752   836   928   946   947   948   954   955   955   955   996   997   998   999    43
         19    258   516   731   774   860   955   955   955   956   956   956   956   956   998   998  1000  1000    53
         20    258   516   731   774   860   955   955   955   956   956   956   956   956   998   998  1000  1000    46
         21    258   516   731   774   860   955   955   955   956   956   956   956   956   998   998  1000  1000    33
         22    258   516   731   774   860   955   955   955   956   956   956   956   956   998   998  1000  1000    26
         23    258   516   731   774   860   955   955   955   956   956   956   956   956   998   998  1000  1000     7
         24    269   538   763   807   897   997   997   997   998   998   998   998   998   998   998  1000  1000    12
```

Figure A-4. DISTRIBUTION OF AIRCRAFT DESTINATIONS AND OVERALL ARRIVAL RATES AS A FUNCTION OF TIME OF DAY

3. DESTINATION ASSIGNMENT

Although it was desired to have the percentage of aircraft, by type, time of day, and weather condition, landing at each airport, this information was not available.

Table 3-1 of Chapter Three gives some of the requisite data for instrument approaches. No corresponding data was available for VFR approaches. Thus, while it can be surmised that, for example, the relative number of general aviation aircraft would materially increase under VFR conditions, more so relatively than air carriers, the factor is unknown. For lack of better information, the data in Table 3-1 was used for both weather conditions.

These data are incorporated in Figure A-4 in the following way. Of the 31283 aircraft arriving in the Boston TCA, 26142 or 83.6 percent, are destined for Logan. It is assumed that this condition prevails when all airports are open. When some of the secondary airports are closed, the percentage will be higher. The first five columns of Figure A-4 correspond to holding fixes serving Logan. Between the hours of 0800 and 1800 all airports are open, and in column five the figure 836, corresponding to 83.6 percent, tells the model to assign that percentage of all aircraft to Logan. These aircraft are assigned to each holding fix on the basis of information supplied by Logan approach control personnel. For those aircraft destined for Logan, the percentages assigned to the five holding fixes are as presented in Table A-3.

Table A-3. PERCENTAGE OF AIRCRAFT BOUND FOR LOGAN ENTERING OVER HOLDING FIXES

Fix	Fix Number	Percentage
Manjo	1	30
Millis	2	30
Bridgewater	3	25
Skipper	4	5
Lawrence	5	10

The figures are then reflected in the cumulative percentages in the first five columns of Figure A-4. For example, Manjo, holding fix number 1 in Figure A-4, gets 30 percent of Logan traffic, thus .3 × .836 = .251, and this number 251 is seen in the first column between the hours of 0800 and 1800. For times of day when some of the secondary airports are closed, the traffic totals were distributed over the airports which were open.

To find a destination, a uniform random number is drawn and is compared for the time of day with the cumulative distributions shown in Figure A-4.

For example, at 0915 the number 943 is drawn. Entering row 10 it can be seen that 928 < 943 ≤ 946, hence the destination is airport number 7 — Beverly.

Columns 1 through 5 correspond, respectively, to Manjo, Millis, Bridgewater, Skipper, and Lawrence. Columns 6 through 17 correspond to Bedford, Beverly, Fitchburg, Fort Devens, Lawrence, Mansfield, Marshfield, Newburyport (Plum Island), Norwood, Plymouth, South Weymouth, and Taunton, respectively. The last column, treated by the program as a default, is Tew-Mac, and shows the hourly rate of total arrivals.

4. ASSIGNMENT OF USER TYPES

Having the destination, the user type can be assigned on the basis of the data in Table 3-1 of Chapter Three. Figure A-5 shows the selection matrix. Its relationship to Table 3-1 can be seen in the following example.

Suppose the destination is Bedford, where 2902 is the total. Of these, 87 or 2.99 percent are air carriers, 235 or 8.09 percent are air taxis, 2425 or 83.56 percent are general aviation, and 155 or 5.34 percent are military. If these percentages are changed to numbers between 0 and 1000, the cumulative distribution is 30, 111, 947, and 1000. Row 6 of Figure A-5 shows, for columns 1, 2, and 3, corresponding to air carrier, air taxi, and general aviation, respectively, the first three of these numbers. Military aircraft are treated as defaults.

Since no VFR data, corresponding to Table 3-1 exists, the matrix corresponding to IFR conditions is identical to Figure A-4.

```
MATRIX HALFWORD SAVEVALUEVFRPT

          COL. 1      2      3

   ROW |  1   782    897    996
       |  2   782    897    996
       |  3   782    897    996
       |  4   782    897    996
       |  5   782    897    996
       |  6    30    111    947
       |  7     0      2    816
       |  8     0      0   1000
       |  9     0      0     38
       | 10     0    190   1000
       | 11     0      0   1000
       | 12     0      0   1000
       | 13     0      0   1000
       | 14     2     11    869
       | 15     0      0   1000
       | 16     0      0    174
       | 17     0      0   1000
       | 18     0    235   1000
```

A/C Destinations

A/C Type (Default = type 4)

Matrix is used to determine aircraft type once destination is known in VFR conditions.

Figure A-5. USER TYPE BY DESTINATION

5. DISTRIBUTION OF WEIGHT CLASS AS A FUNCTION OF TYPE

Table A-4 presents aircraft distribution data derived from information supplied by TSC, and based in part on FAA equipment forecast for air carrier operations at Logan. The weight classes were assigned to the forecast aircraft types in accordance with Appendix 3 to Reference 5. The figures are approximations; therefore, before the model is used for analysis, they should be verified.

Table A-4. FREQUENCY DISTRIBUTION OF AIRCRAFT WEIGHT CLASSES

Type	Weight Class		
	Small	Large	Heavy
Air Carrier	0	.9	.1
Air Taxi	.1	.9	0
General Aviation	.9	.1	0
Military	.02	.9	.08

6. DISTRIBUTION OF APPROACH CATEGORY AS A FUNCTION OF TYPE

Table A-5 presents approach category data which was also based on information supplied by TSC. The figures are approximations; therefore, before the model is used for analysis, they should be verified.

Table A-5. FREQUENCY DISTRIBUTION OF AIRCRAFT APPROACH CATEGORIES

Type	Approach Category			
	A	B	C	D
Air Carrier	0	.05	.1	.85
Air Taxi	.9	.1	0	0
General Aviation	.9	.07	.03	0
Military	.1	.3	.3	.3

Table A-4 is combined with Table A-5 as a single input matrix, and is displayed in Figure A-6. The data are shown as cumulative probability distributions.

MATRIX HALFWORD SAVEVALUECATWT

ROW A/C Type	COL. 1	2	3	4	5	6	7	
1	0	0	787	1000	0	787	1000	Air Carrier
2	0	1000	1000	1000	0	1000	1000	Air Taxi
3	1000	1000	1000	1000	1000	1000	1000	General Aviation
4	300	500	1000	1000	500	1000	1000	Military
	Approach Category				Weight Class			

Matrix is used to define aircraft category and weight, once type has been determined.

Figure A-6. CUMULATIVE FREQUENCY DISTRIBUTION OF AIRCRAFT APPROACH CATEGORIES AND WEIGHT CLASSES

7. ROUTE DISTANCES FROM HOLDING FIXES TO LOGAN UNDER RADAR AND NONRADAR (VORTAC) ENVIRONMENTS

The distance tables are shown in Figures A-7 and A-8 as program input matrices. The numbers in row 6 (Figure A-8) define the matrices that carry airport data.

8. DISTANCES FROM SECONDARY AIRPORTS TO LOGAN

The distances from the secondary airports to Logan are also shown in Figures A-7 and A-8.

9. MINIMA FOR EACH APPROACH SERVING EACH RUNWAY BY APPROACH CATEGORY

Ceiling-visibility and landing approach data are tabulated for each runway at each airport. Table A-6 shows these minima for Logan, and Figure A-9 shows the same data displayed as they are presented to the computer except that the order of the runways is different. In Table A-6, different minima are shown for the same type of approach on different runways. This is because the minima depend on whether a straight-in or circling approach is used.

10. *IDENTITY OF ALL FACILITIES NECESSARY FOR EACH APPROACH AT EACH RUNWAY*

Table A-7 was compiled by examination of the Instrument Approach Procedure Charts, and defines those facilities which are necessary for a particular approach. The numbers are either zero or non-zero. A zero indicates that the facility is not necessary. A non-zero entry is the number of the facility as carried in the Facility Status File.

MATRIX HALFWORD SAVEVALUEDSTNR

	COL. 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
ROW 1	26	49	39	55	26	15	14	38	49	27	34	31	27	28	31	28	45	24
2	38	39	39	38	36	38	21	62	55	38	45	31	35	38	42	28	45	35
3	26	38	46	26	43	26	14	49	45	27	55	41	27	48	52	38	55	24
4	19	18	29	25	39	45	35	66	62	51	34	21	48	28	31	17	34	45
5	27	38	29	44	27	15	24	38	48	28	42	55	38	28	58	38	52	17

Same as DSTN matrix

Figure A-7. DISTANCE TABLE HOLDING FIXES AND SECONDARY AIRPORTS TO PRIMARY AIRPORT - RADAR DOWN

MATRIX HALFWORD SAVEVALUE DSTN

			Hold Areas					Secondary Airport												
			COL. 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Logan Runways	ROW 1	4	34	25	19	31	49	27	36	46	39	46	22	29	55	12	33	14	30	38
	2	27	39	45	41	18	33	16	22	37	31	25	22	29	34	12	33	14	30	38
	3	22	33	45	41	20	26	26	16	38	43	23	47	36	28	43	45	35	49	24
	4	33	50	29	25	20	44	43	35	68	63	43	29	20	40	26	29	30	32	49
	5	15	25	32	47	41	26	16	22	37	31	25	36	51	34	34	55	35	52	17
	6		101	101	101	101	101	106	107	108	109	110	111	112	113	114	115	116	117	118

Airport
definition
matrix
number (Row)

Distance from hold area/secondary airport to Logan in a radar environment

Column Headings

1	Manjo	10	Lawrence
2	Millis	11	Mansfield
3	Bridgewater	12	Marshfield
4	Skipper	13	Newburyport
5	LWM	14	Norwood
6	Bedford	15	Plymouth
7	Beverly	16	S. Weymouth
8	Fitchburg	17	Taunton
9	Ft. Devens	18	Tew-Mac

Figure A-8. DISTANCE TABLE HOLDING FIXES AND SECONDARY AIRPORTS TO PRIMARY AIRPORT - RADAR UP

Table A-6. RUNWAY APPROACH MINIMA

Approach	Runway					Approach Category
	27	22L	33L	4R	15R	
VOR	460 - 1	680 - 1	680 - 01	680 - 01	680 - 1	A
	460 - 1	680 - 1	680 - 01	680 - 01	680 - 1	B
	460 - 1	820 - 1-1/2	820 - 1-1/2	820 - 1-1/2	820 - 1-1/2	C
	460 - 1	820 - 2	820 - 2	820 - 2	820 - 2	D
VOR DME	680 - 1	560 - 1	560 - 1	560 - 1	780 - 1	A
	680 - 1	560 - 1	560 - 1	560 - 1	780 - 1-1/4	B
	820 - 1-1/2	560 - 1	560 - 1	560 - 1	780 - 1-1/2	C
	820 - 2	560 - 1-1/4	560 - 1-1/2	560 - 1-1/2	780 - 1-3/4	D
ILS	680 - 1	680 - 1	680 - 1	216 - 1/2	268 - 3/4	A
	680 - 1	680 - 1	680 - 1	216 - 1/2	268 - 3/4	B
	820 - 1-1/2	820 - 1-1/2	820 - 1-1/2	216 - 1/2	268 - 3/4	C
	820 - 2	820 - 2	820 - 2	216 - 1/2	268 - 3/4	D
LOC	680 - 1	680 - 1	820 - 2	466 - 3/4	580 - 1	A
	680 - 1	680 - 1	820 - 2	466 - 3/4	580 - 1	B
	820 - 1-1/2	820 - 1-1/2	820 - 2	466 - 3/4	580 - 1	C
	820 - 2	820 - 2	820 - 2	466 - 3/4	580 - 1-1/4	D
NDB	680 - 1	680 - 1	680 - 1	680 - 1	680 - 1	A
	680 - 1	680 - 1	680 - 1	680 - 1	680 - 1	B
	820 - 1-1/2	820 - 1-1/2	820 - 1-1/2	820 - 1-1/2	820 - 1-1/2	C
	820 - 2	820 - 2	820 - 2	820 - 2	820 - 2	D
LOC BC	680 - 1	420 - 1	420 - 1	420 - 1	420 - 1	A
	680 - 1	420 - 1	420 - 1	420 - 1	420 - 1	B
	820 - 1-1/2	420 - 1	420 - 1	420 - 1	420 - 1	C
	820 - 2	420 - 1	420 - 1	420 - 1	420 - 1	D
ASR	460 - 1	540 - 1	480 - 1/2	620 - 1/2	800 - 1	A
	460 - 1	540 - 1	480 - 1/2	620 - 1/2	800 - 1-3/4	B
	460 - 1	540 - 1	480 - 1/2	620 - 1/2	800 - 1-1/2	C
	460 - 1	540 - 1-1/4	480 - 1	620 - 1	800 - 1-3/4	D

Figure A-10 displays the same data in the form of the program input matrix. The first four columns show those facilities essential to the approach. The last four columns are facilities which, if down, have only the effect of raising the minima for the approach, as prescribed by FAA regulations.

It is possible that a different set of facilities may define the same approach on the same runway. For example, when lacking a DME, the necessary fixes can be established either with another DME or from bearing information solely. For this reason, the model contains more than one matrix of the form of Figure A-10. The separate entries are a requirement to maintain unique program look-up logic.

MATRIX FULLWORD SAVEVALUE MINMA

		COLUMN	(4R) 1	(27) 2	(22L) 3	(33L) 4	(15R) 5
	ROW		Runway Number				
VOR 1	1	1	680100	460100	680100	680100	680100
	2	2	680100	460100	680100	680100	680100
	3	3	820150	460100	820150	820150	820150
	4	4	820200	460100	820200	820200	820200
VOR DME 2	5	1	680100	680100	560100	680100	780100
	6	2	680100	680100	560100	680100	780125
	7	3	820150	820150	560100	820150	780150
	8	4	820200	820200	560125	820200	780175
ILS 3	9	1	216050	680100	680100	680100	268075
	10	2	216050	680100	680100	680100	268075
	11	3	216050	820150	820150	820150	268075
	12	4	216050	820200	820200	820200	268075
LOC 4	13	1	460075	680100	680100	680100	580100
	14	2	460075	680100	680100	680100	580100
	15	3	460075	820150	820150	820150	580100
	16	4	460075	820200	820200	820200	580125
NDB 5	17	1	680100	680100	680100	680100	680100
	18	2	680100	680100	680100	680100	680100
	19	3	820150	820150	820150	820150	820150
	20	4	820200	820200	820200	820200	820200
LOC BC 6	21	1	680100	680100	420100	680100	680100
	22	2	680100	680100	420100	680100	680100
	23	3	820150	820150	420100	820150	820150
	24	4	820200	820200	420100	820200	820200
ASR 7	25	1	620050	460100	540100	480050	800100
	26	2	620050	460100	540100	480050	800175
	27	3	620050	460100	540100	480050	800150
	28	4	620100	460100	540125	480100	800175

Approach Type

A/C Category

Minimum ceiling requirement (in feet)

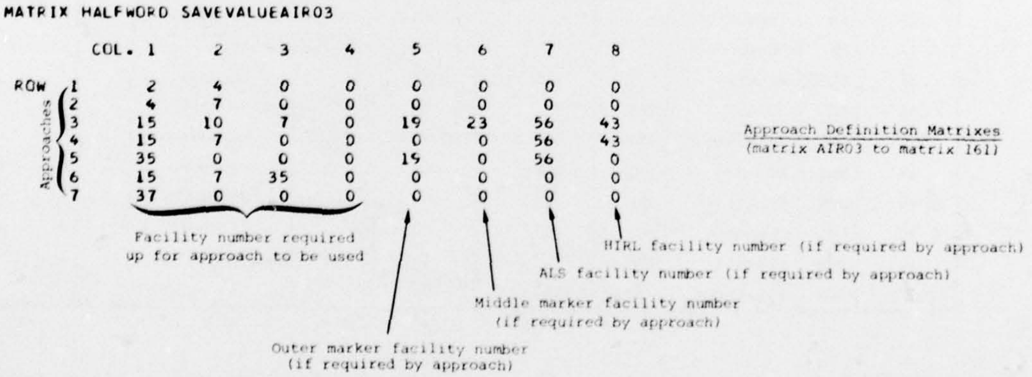
Minimum visibility requirement (in 100ths of a mile)

Logan Minima Matrix

Figure A-9. LANDING APPROACH MINIMA

Table A-7. FACILITY-APPROACH DEFINITIONS -- BOSTON (LOGAN), RUNWAY 4R

Facility	ID	Frequency	Approach Type						
			1	2	3	4	5	6	7
			VOR	VOR DME	ILS	LOC	NDB	LOC BC	ASR
LOC	I-BOS	110.3	0	0	15	15	0	15	0
LOC	I-LIP	110.7	0	0	0	0	0	0	0
LOC	I-MDC	110.7	0	0	0	0	0	0	0
GS			0	0	0	0	0	0	0
GS			0	0	10	0	0	0	0
GS			0	0	0	0	0	0	0
VOR	HTM	109.0	2	0	0	0	0	0	0
VOR	BOS	112.7	4	4	0	0	0	0	0
VOR	LWM	112.0	0	0	0	0	0	0	0
VOR	MHT	114.2	0	0	0	0	0	0	0
DME	BOS	Ch.27	0	7	7	7	0	7	0
NDB	SEW	382	0	0	0	0	35	35	0
ASR-7			0	0	0	0	0	0	37
LOM			0	0	19	0	19	0	0
MM			0	0	23	23	0	0	0
ALS			0	0	56	56	56	0	0
HIRL			0	0	43	43	0	0	0



```
MATRIX HALFWORD SAVEVALUEAIR03

        COL. 1     2     3     4     5     6     7     8

ROW  1       2     4     0     0     0     0     0     0
     2       4     7     0     0     0     0     0     0
     3      15    10     7     0    19    23    56    43
     4      15     7     0     0     0     0    56    43
     5      35     0     0     0    19     0    56     0
     6      15     7    35     0     0     0     0     0
     7      37     0     0     0     0     0     0     0
```

Figure A-10. APPROACH DEFINITION MATRIX

11. MTBF AND MTTR FOR FACILITY STATUS FILE

These two failure and repair parameters are required for each of the following facilities or functions. Table A-8* shows the facilities carried in the Facility Status File. Figure A-11 shows the program matrix.

Table A-8. FACILITY FILE

Facility Number	Type	Location	ID	Frequency	Facility Number	Type	Location	ID	Frequency
1	VOR	Lawrence	LWM	112.0	33	SDF	Beverly	BVY	108.7
2	VOR	Whitman	HTM	109.0	34	SDF	Norwood	OWD	108.3
3	VOR	Manchester	MHT	114.2	35	NDB	Boston	SEW	382
4	VOR	Boston	BOS	112.7	36	TACAN	S. Weymouth	IAF	Ch.67
5	DME	Whitman		Ch.27	37	ASR	Boston		
6	DME	Manchester		Ch.89	38	ARSR	Boston		
7	DME	Boston		Ch.74	39	SECRA	Boston		
8	GS	Bedford			40	ARTS-3	Boston		
9	GS	Boston 15R			41	HIRL	Lawrence 5		
10	GS	Boston 4R			42	HIRL	Lawrence 23		
11	GS	Boston 33L			43	HIRL	Boston 4R		
12	LOC	Bedford	I-BED	109.5	44	HIRL	Boston 22L		
13	LOC	Lawrence	I-LWM	111.7	45	HIRL	Boston 15R		
14	LOC	Boston 15R	I-MDC	110.7	46	HIRL	Boston 33L		
15	LOC	Boston 4R	I-BOS	110.3	47	HIRL	Boston 9		
16	LOC	Boston 33L	I-LIP	110.7	48	HIRL	Boston 27		
17	LOM	Bedford	BE	332	49	FDEA	Boston		
18	LOM	Boston 15R	MD	375	50	DEDS	Boston		
19	LOM	Boston 4R	BO	221	51	FM	Beverly		
20	LOM	Boston 33L	LI	346	52	FM	Norwood		
21	MM	Bedford			53	NDB	Bedford	SKR	251
22	MM	Boston 15R			54	HIRL	Lawrence 5		
23	MM	Boston 4R			55	HIRL	Lawrence 23		
24	MM	Boston 22L			56	ALS	Boston 4R		
25	NDB	Beverly	TOF	269	57	ALS	Boston 33L		
26	NDB	Devens	DKO	352	58	HIRL	S. Weymouth 8		
27	NDB	S. Weymouth	IAF	236	59	HIRL	S. Weymouth 26		
28	NDB	Tew-Mac	HRX	402	60	HIRL	S. Weymouth 17		
29	NDB	Taunton	TAN	227	61	HIRL	S. Weymouth 35		
30	NDB	Plymouth	PYM	257	62	ALS	S. Weymouth 26		
31	NDB	Norwood	SOG	201	63	HIRL	Bedford 22		
32	NDB	Fitchburg	FIT	206					

---

*The data source is "Air Navigation and Air Traffic Control Facility Performance and Availability" (RIS:SM 6040-20), Report for Calendar Year 1975, prepared by the Airways Facilities Service, FAA, Washington, D.C.

MTBF in minutes

MTTR in minutes

```
MATRIX FULLWORD SAVEVALUE FACIL

               COLUMN  1          2            3

ROW  1                 1      60300          318
     2                 1      60300          318
     3                 1      60300          318
     4                 1      60300          318
     5                 1      72300          402
     6                 1      24600          534
     7                 1      24600          534
     8                 1      28500         1260
     9                 1      28500         1260
    10                 1      28500         1260
    11                 1      28500         1260
    12                 1      23400          900
    13                 1      23400          900
    14                 0      23400          900
    15                 0      23400          900
    16                 0      23400          900
    17                 0     111900         1920
    18                 0     111900         1920
    19                 0     111900         1920
    20                 0     111900         1920
    21                 0     130500         2580
    22                 0     130500         2580
    23                 0     130500         2580
    24                 0     130500         2580
    25                 0    2100000          660
    26                 0    2100000          660
    27                 0    2100000          660
    28                 0    2100000          660
    29                 0    2100000          660
    30                 0    2100000          660
    31                 0    2100000          660
    32                 0    2100000          660
    33                 0    2100000          660
    34                 0    2100000          660
    35                 0    2100000          660
    36                 0      24600          534
    37                 0      36300           96
    38                 0       5160          180
    39                 0      29100          120
    40                 0      20100          114
    41                 0      25200          780
    42                 0      25200          780
    43                 0      25200          780
    44                 0      25200          780
    45                 0      25200          780
    46                 0      25200          780
    47                 0      25200          780
    48                 0      25200          780
    49                 0    2100000          616
    50                 0    2100000          616
    51                 0    2100000          660
    52                 0    2100000          660
    53                 0    2100000          660
    54                 0      25200          780
    55                 0      25200          780
    56                 0      25200          780
    57                 0      25200          780
    58                 0      25200          780
    59                 0      25200          780
    60                 0      25200          780
    61                 0      25200          780
    62                 0      25200          780
    63                 0      25200          780
```

Facility Number

Facility Status: 1-facility up; 0-facility down

Facility Status Matrix

Figure A-11. FACILITY STATUS FILE

12. TABLE OF TRAIL SEPARATION AND NUMBERS OF AIRCRAFT PER CONTROLLER

Table 3-2 in Chapter Three lists the data used in this model. Figure A-12 shows the same data as an input matrix.

MATRIX HALFWORD SAVEVALUEARSEP

	ROW	COL. 1	2	3	4	5	6	7	8	9	10	11
Radar Conditions	1	37	39	40	38	3	1	2	3	0	1	20
	2	37	39	40	0	3	1	2	3	0	1	20
	3	37	39	0	38	3	1	2	3	0	1	16
	4	37	39	0	0	3	1	2	3	0	1	16
	5	37	0	40	38	4	0	1	2	0	0	10
	6	37	0	40	0	4	0	1	2	0	0	10
	7	37	0	0	38	4	0	1	2	0	0	12
	8	37	0	0	0	4	0	1	2	0	0	12
	9	0	39	40	38	3	1	2	3	0	1	20
	10	0	39	40	0	3	1	2	3	0	1	20
	11	0	39	0	38	5	0	0	1	0	0	16
	12	0	39	0	0	5	0	0	1	0	0	16
	13	0	0	40	38	5	0	0	1	0	0	10
	14	0	0	0	38	5	0	0	1	0	0	8
Non-Radar Conditions	15	0	0	40	0	12	0	0	1	0	0	10
	16	0	0	0	0	12	0	0	1	0	0	8

Columns 1–4: Equipment required up to determine which separation criteria to use (row number)

Column 5: Required separation in miles

Columns 6–10: Additional separation in miles for various weights of aircraft

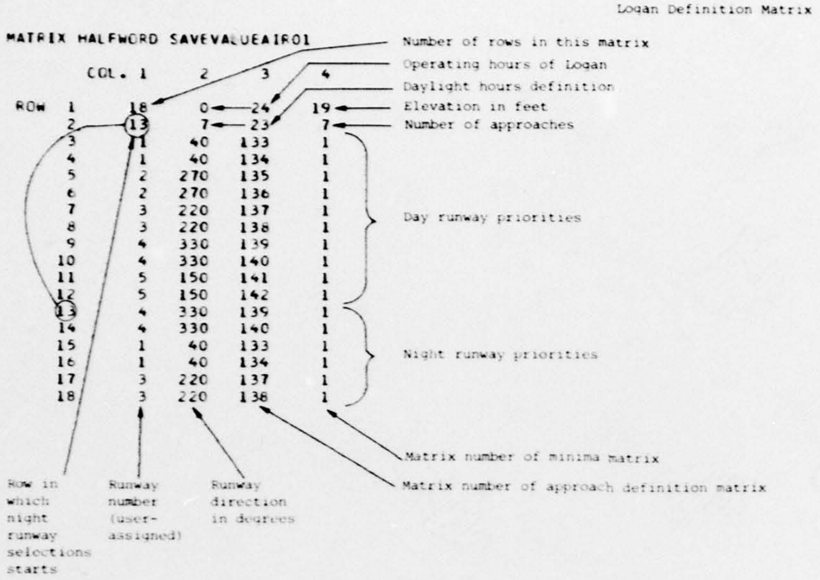
Column 11: Number of aircraft air control can handle at one time

Figure A-12. SEPARATION MATRIX

13. AIRPORT DEFINITION DATA

Figure A-13 displays the matrix used by the model to define the airport layout. Two different matrix formats are used, one for a principal airport such as Logan, and another for the secondary airports. The matrices are self-explanatory. One note of importance is that the field elevation number is used in conjunction with the minima tables to determine ceiling heights above the ground.

Logan Definition Matrix



MATRIX HALFWORD SAVEVALUEAIR01

ROW	COL. 1	2	3	4
1	18	0	24	19
2	13	7	23	7
3	1	40	133	1
4	1	40	134	1
5	2	270	135	1
6	2	270	136	1
7	3	220	137	1
8	3	220	138	1
9	4	330	139	1
10	4	330	140	1
11	5	150	141	1
12	5	150	142	1
13	4	330	139	1
14	4	330	140	1
15	1	40	133	1
16	1	40	134	1
17	3	220	137	1
18	3	220	138	1

Airport Definition Matrix (General Case)

	Row \ Column	1	2	3	4
	1	Number of Rows (n)	Opening Time	Closing Time	Elevation (in feet)
	2	Night Runways (M)	Day Start	Night Start	Number of Approaches
Day matrix	3 . . M-1	Runway Number (Consecutive)	Runway Direction (Degrees)	Approach Matrix Number	Minima Matrix Number
Night matrix	M . . n	↓	↓	↓	↓

Figure A-13. FIELD DEFINITION MATRIX

APPENDIX B

REFERENCES

1. "Special Ceiling-Visibility Wind Tabulation" for Boston, for the period January 1970 to December 1974, National Climatic Center, Asheville, North Carolina.
2. "Seasonal and Annual Persistence of Surface Wind Direction by Wind Speed" at Binghamton, New York, for the period January 1960 to December 1964, National Climatic Center, Asheville, North Carolina.
3. "Duration of High Surface Wind Speeds" at Oscoda, Michigan AFB, for the period November 1950 to December 1970, National Climatic Center, Asheville, North Carolina.
4. "FAA Air Traffic Activity, Calendar Year 1975", March 1976, U.S. Department of Transportation, FAA, Office of Management Systems, Information and Statistics Division, Washington, D.C. 20591.
5. *Air Traffic Control*, 7110.65, 1 January 1976, U.S. Department of Transportation, FAA, Air Traffic Service, Washington, D.C. 20591.
6. "Instrument Approach Procedures", National Ocean Survey.
7. "Standard Operating Procedures", March 15, 1976, (BOS TWR 7110.35), Boston Tower, Logan International Airport, East Boston, Massachusetts.
8. "60-Nautical-Mile Video Map", ASR-7, National Ocean Survey, revised 4 February 1976, Boston (Logan International), Massachusetts.
9. "Performance Measurement System for Major Airports", November 1975, U.S. Department of Transportation, FAA, Air Traffic Service, Operation Research Branch, Washington, D.C. 20591.
10. "Air Navigation and Air Traffic Control Facility Performance and Availability" (RIS: SM 6040-20), Calendar Year 1975, FAA, Airway Facilities Service, Washington, D.C. 20591.

APPENDIX C

REPORT OF NEW TECHNOLOGY

No patents of inventions were generated under this contract. However, the effort did advance the state of the art in aviation system modeling. The major development was the integration into one model of the numerous elements that affect aircraft delays; namely: FAA facility availabilities, aircraft traffic levels, air traffic control procedures, aircraft performance, and weather. A related development involved the formulation of a cost model for estimating the manpower costs associated with maintaining FAA facilities.

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